The Friction Acting on the Slipform of a Continuous Tunnel Boring Machine

by

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Submitted to the Department of Mechanical Engineering
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Abstract

The development of Tunnel Boring Machine (TBM) has provided a much safer working environment for workers and engineers to do the tunneling, and the new concept of a Continuous Tunnel Boring Machine (CTBM) has been generated to improve it to a larger extent. It was performed by excavating the tunnel and extruding a continuous concrete liner simultaneously by the CTBM. This machine is designed to pump out concrete at a pressure of 250psi. The concrete will work as a propulsive force at the beginning, and will harden after 2 hours to support the tunnel after the CTBM goes through.

The purpose of this research is to perform a friction test between the pumped concrete and the slipform of the CTBM. Pressure applied by the earth on the concrete liner may be about 300 psi for a 300 ft deep tunnel in dense sand, and it can cause a big drag force acting on the slipform from the hardened concrete. The fresh concrete is liquid and does not cause much drag force on the machine. The friction between hardening concrete and the slipform is the most difficult part to predict. We have constructed a test device to simulate the conditions of the tunnel underground and test the friction under these conditions.

A twenty foot long testing device is built to simulate the real forty foot long CTBM, and hydraulic cylinders are used to simulate the pressure from the earth. Concrete is pumped into the device continuously analogous to the real machine, a sixteen foot long strip of steel is used to simulate the slipform of the CTBM, and the strip will be pulled out of the concrete by a motor at a speed of 0.5 in/min to 2 in/min. A load cell is connected to the pulling chain to record the drag force. From the history of the drag force during the 2-5 hour test, the distribution of the friction along the length of the slipform in different hardened condition is determined, and the results can be used to polish the design of the CTBM.

Thesis Supervisor: Carl R. Peterson
Title: Professor

Acknowledgments

I would like to thank my thesis advisor Professor Carl R. Peterson for his general guidance and advice to help me complete this thesis project. His knowledge and enthusiasm towards the project has strongly influenced me and opened a deeper space for me in Mechanical Design. I want to thank him all those suggestions during my struggling with the design and manufacturing of the testing apparatus for this research. I would like to thank Professor Herbert H. Einstein in Civil Engineering. His assistance helps me greatly in understanding the structure of the tunnel underground's and the features of the concrete I handled in this research. Special thanks go to my family in Taiwan for their strong support for my graduate study abroad. I want to thank Jane for being with me through all the time when I struggled. For all my friends who help me and encourage me during the two years of study in MIT, thank you all.

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Chapter 1

Introduction

In this thesis, a testing apparatus is constructed to simulate the advancing slipform of a Continuous Tunnel Boring Machine (CTBM) underground. The experiments were designed to measure the friction between the slipform and the concrete extruded around it under the pressure from the earth. In chapter one, the basic concept of the CTBM and the objectives of this research will be discussed. Chapter two will introduce the background of this research, including the conceptual design of the system and some research that has been done in Civil Engineering about the behavior of the concrete and concrete liner of a tunnel under the pressure of the earth.

In chapter three, the design of the testing apparatus, including the whole system and some critical details or ideas in this design is discussed. Chapter four covers the details of the concrete mix which has been utilized in the experiments. Chapter five discusses the procedures of conducting the test experiment. In chapter six, experimental results of those tests will be analyzed, including the discussion of error and the performance of the testing device. Chapter seven provides suggestions to the future design of the CTBM based on the experimental results completed in this research.

The design drawings and calculations of the parts are shown in appendix A, B, and C. the commercial catalogs are shown in appendix D, and the testing records are shown in appendix E.

1.1 The Concept of CTBM

The hazardous and highly unpredictable working environment of tunnel excavation has been improved from conventional tunneling, which was accomplished by hand excavating, drilling, and blasting, by the application of the Tunnel Boring Machine (TBM) and Tunnel Cutting Machine. In this research, we will consider the TBM only. The TBM provides a much safer and more reliable working environment than the conventional methods specifically under soft ground. The new concept of a CTBM is generated to improve the situation to a larger extent. This machine excavates the ground and simultaneously extrudes a continuous concrete liner. After the machine goes through, a tunnel is built and supported by cured high early strength concrete. This new machine can accomplish the task of tunneling by a simpler and less expensive method and better performance tunnels than the traditional TBM.

The traditional TBM's are typically divided into two categories[10]. The first type TBM works in hard rocks and the excavated tunnel supports itself without the need of a concrete liner. A schematic drawing of the typical concept of the this type of TBM without the conveyor and power supply systems is shown in Figure 1-1.

Figure 1-1 explains the standard processes of boring tunneliing as the machine advances:

1. supporting hydraulic cylinders (3) extend out, apply force on the hard rock (4), and provide the normal force for necessary static friction needed for advancing.

2. propulsive hydraulic cylinders (2) extend out, apply force on the cutter head (1) against the rock in front of it

3. cutter head is driven by motors (usually hydraulic motors) and rotates, crushes rocks and excavates the tunnel until the propulsive hydraulic cylinders are fully extended

4. stop the machine, retrieve supporting hydraulic cylinders, retrieve propulsive hydraulic cylinders to bring the body of the machine forward

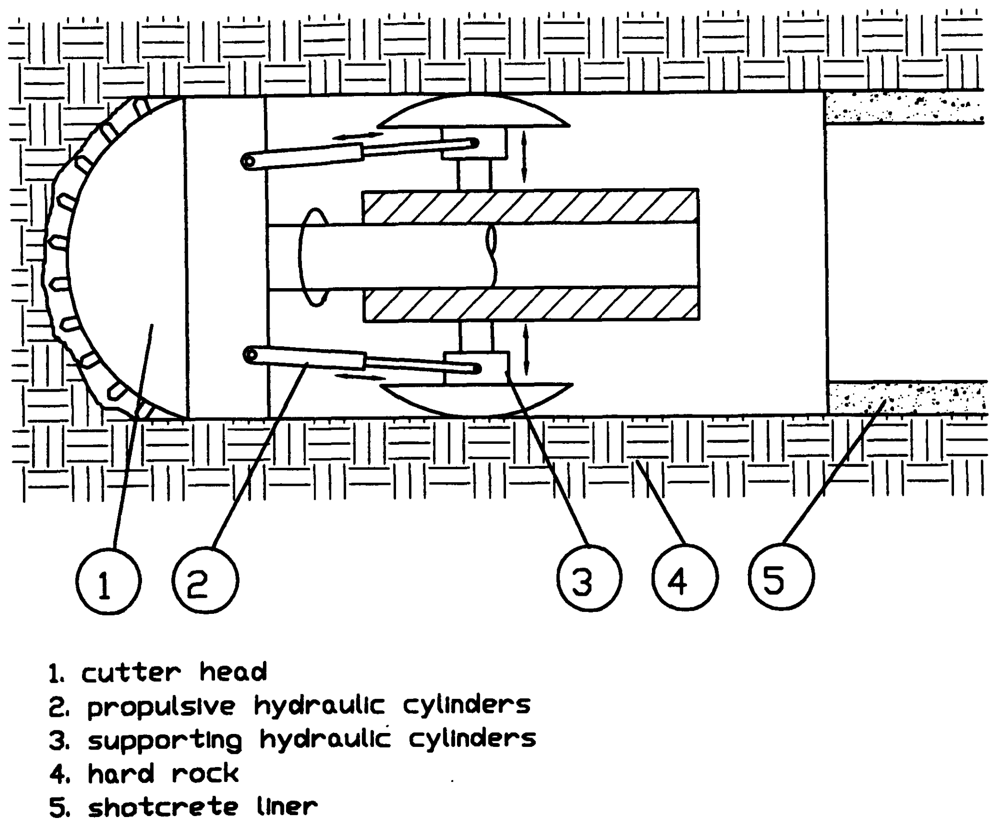


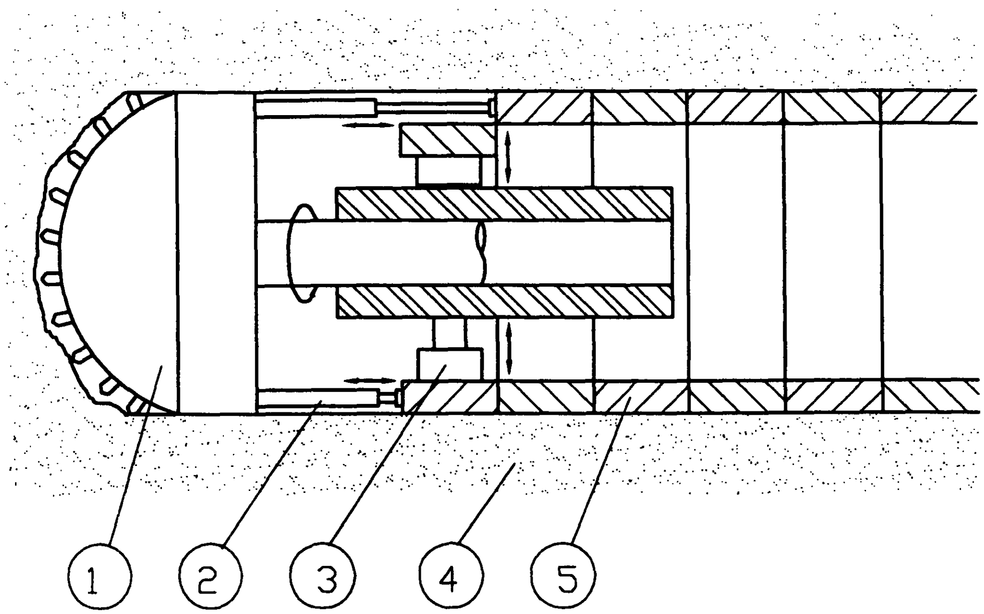
Figure 1-1: A TBM designed to work in hard rocks

5. start again from step 1

The rock should be strong enough to support itself without collapsing. However, a shotcrete liner can be pumped against the wall if necessary for the reason of safety. Shotcrete is a mix concrete with 15-20 % cement, 30-40% coarse aggregate, and 40-50% fine aggregate by weight, and chemical admixture (accelerator). It is mixed and pumped to spray on the wall to provide support strength to the tunnel, but it causes a dangerous environment harmful for workers because the shotcrete will rebound and the powder of cement in the air is corrosive to people's skin.

The other type of TBM is designed to work in softer ground that has to be supported by concrete liners. In certain situations, Shield Machines are used in very soft ground to build the so-called earth tunnels. The schematic configuration of the second type TBM and Shield Machines without the conveyor and power supply sytems is shown in Figure 1-2. The standard operating processes advancing are:

1. prepare some precured concrete liner segments (5) prior to the tunnel boring



1. cutter head
2. propulsive hydraulic cylinders
3. feeding hydraulic cylinders
4. soft ground
5. precured liner block

Figure 1-2: A TBM designed to work in soft ground

2. propulsive hydraulic cylinders (2) extend against the concrete liner to apply force on the cutter head (1) against the ground in front, and provide the essential pressure for cutters to excavate the ground

3. cutter head is driven by motors (usually hydraulic motors) to excavate the ground, and advances forward until the propulsive hydraulic cylinders are fully extended

4. when the propulsive hydraulic cylinders are fully extended, the erectors (3) should already have been retrieved and ready to to feed the precured liner segments

5. retrieve half of the propulsive hydraulic cylinders, extend the erectors to feed the concrete blocks, and then repeat the process on the other half (usually there are 6-10 segments are required to form a circle of liner)

6. workers lock the fed concrete segments together to form a liner to support the

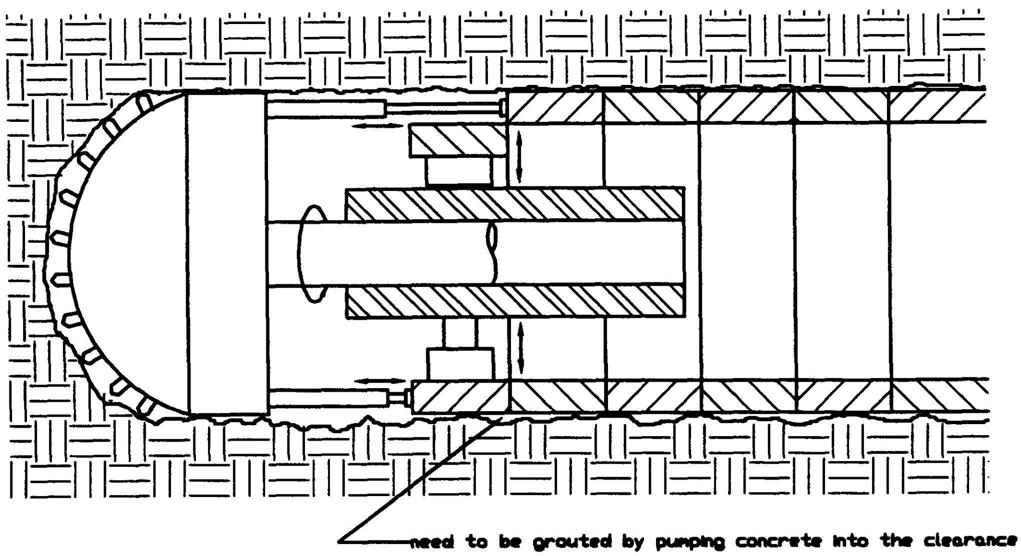


Figure 1-3: The clearance between ground and concrete liner

tunnel

7. start again from step 1 till breaking through

Compared to the first type of TBM, the second type of TBM is more expensive because of the need of precured concrete liner blocks. In soft ground, the first type TBM is not a good solution because it does not have any protection for the workers when the shotcrete has not cured and becomes strong enough to support the tunnel if it is going to collapse.

Furthermore, in the real situation, the tunnels as bored are never perfectly round, some clearance between the ground and the precured concrete liners in the second type TBM happens as shown in Figure 1-3. Load concentration in this situation can cause the failure of the liner. Under this circumstances, postprocessing called grouting is required. Usually, the segments of concrete liners have grouting pipes built in. The workers can start pumping mortar into the clearance after the machine goes through.

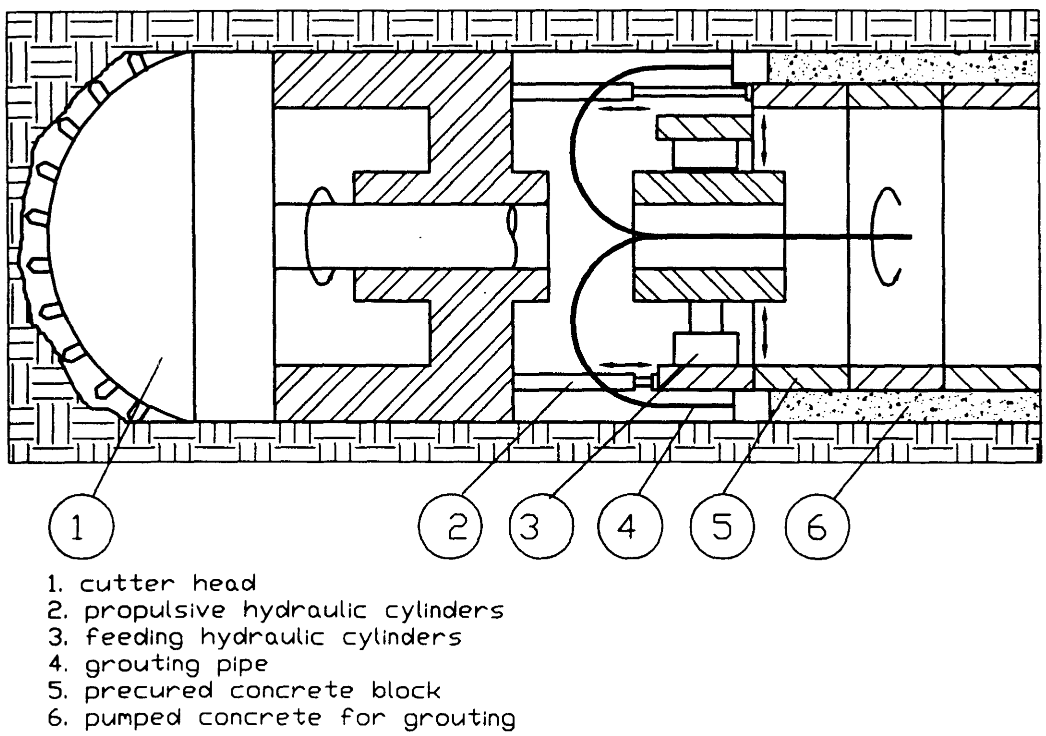


Figure 1-4: A TBM designed to grout at the same time

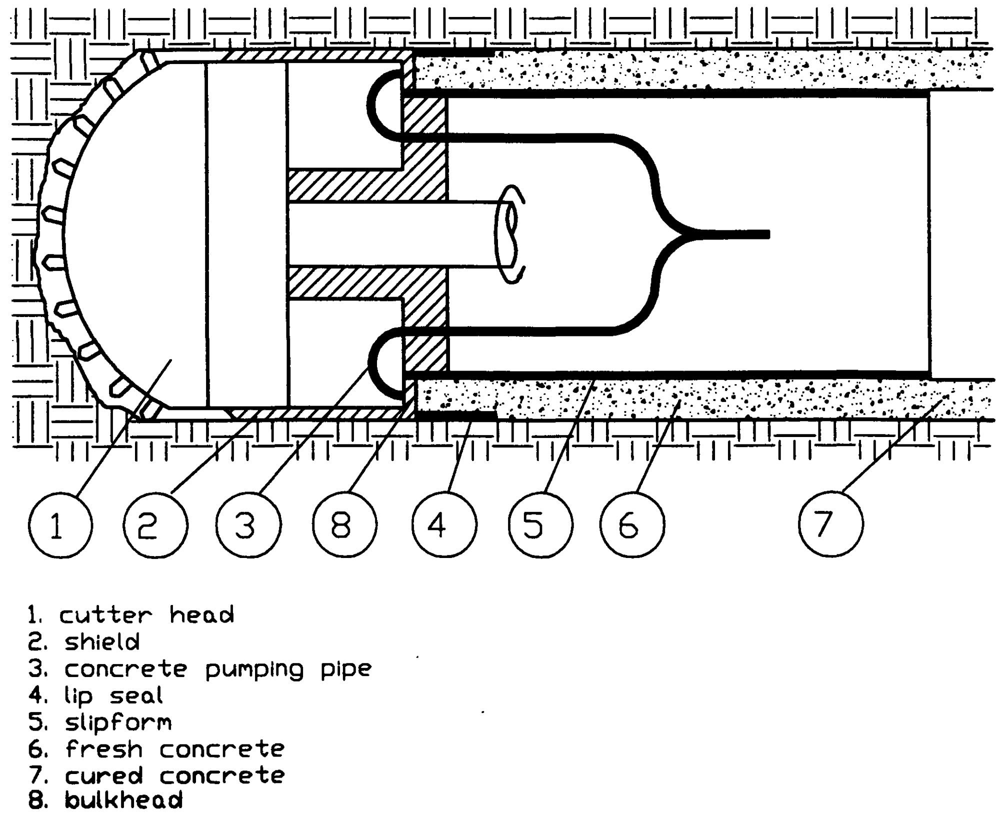


Figure 1-5: The concept of CTBM

Another way to improve the efficiency of tunneling of the second type TBM's or the Shield Machines is to pump mortar into the clearance directly from the machine, as shown in Figure 1-4.

The concept of the CTBM is generated to simplify the processes of tunnelling and building a liner. It also improves the quality of the liner, reduces the cost, and provides a safer working environment for workers and engineers. The schematic drawing of the concept of CTBM is shown in Figure 1-5.

There are no discrete steps to operate the CTBM because it is continuous. It extrudes high early strength concrete or continuously from the pumping pipe (3) at up to 250psi, which acts against a bulkhead (8) to generate the propulsive force of this machine. When the machine goes through, the concrete liner left behind is 2-3 hour old and becomes strong enough to support the tunnel. The lip seal shown in the drawing is designed to prevent concrete from flowing forward to the cutter head

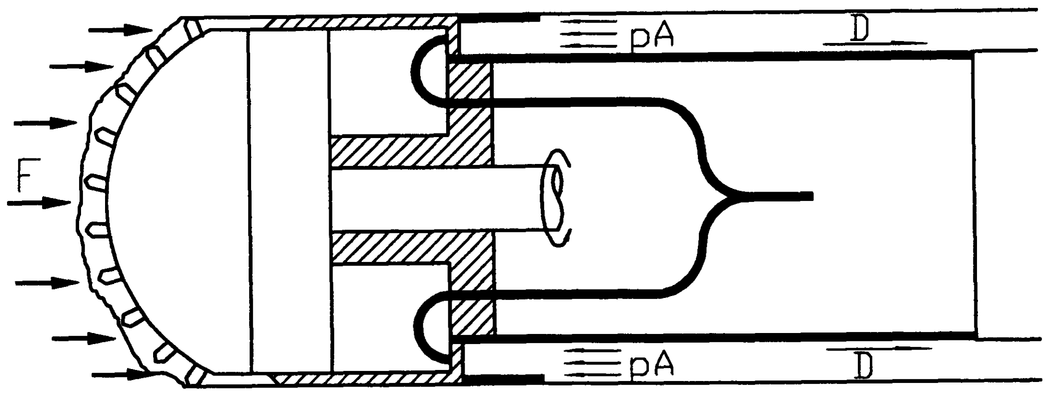


Figure 1-6: The force balance of a CTBM

and causing damage to the cutters.

The basic advantages of a CTBM include [8]:

- one-pass continuous operation
- elimination of traditional wall jacking system
- continuous support of tunnel and elimination of primary support
- elimination of precured liner segments and grouting
- improved efficiency of machine and labor, yielding cost savings
- no cement powder flying around

The advance of the CTBM is accomplished by the extrusion of the concrete as shown in Figure 1-6, where

F: cutting thrust

p: pumped concrete pressure

A: area of the bulkhead

D: drag force, mostly from the friction between slipform and shotcrete liner

The thrust of the concrete has to overcome the drag force and provide the cutting thrust for the cutting disks on the cutting head.

$$p(pressure)A(area) - D(drag) = F(thrust)$$

1.2 Previous Work

1.2.1 Research done by Marsh

[8]

A thesis of "Concepts for the Integration of Tunnel Excavation and Ground Support Systems" was done by Eric Russel Marsh directed by Professor Carl R. Peterson in 1992 in MIT Mechanical Engineering Department. It covers the conceptual design of the steering, slipform, conveyor system, cutter head system, and the machine chassis. Furthermore, the operation, including starting up, shutting down, progressing, and breaking through, is discussed. The design of the CTBM in his research is shown in Figure 1-7.

The hydraulic cylinders shown in the design will be used when the machine is shut down. They can move forwards and backwards slowly to prevent the binding of the curing concrete and the slipform. They can also be used to provide the necessary thrust force when the machine encounters extremely hard rock layers underground.

1.2.2 Research done by Gupta

[6]

A thesis of "Performance Prediction and Conceptual Design of a Continuous Tunnel Boring Machine" was done by Ajay Gupta directed by Professor Herbert H. Ein-

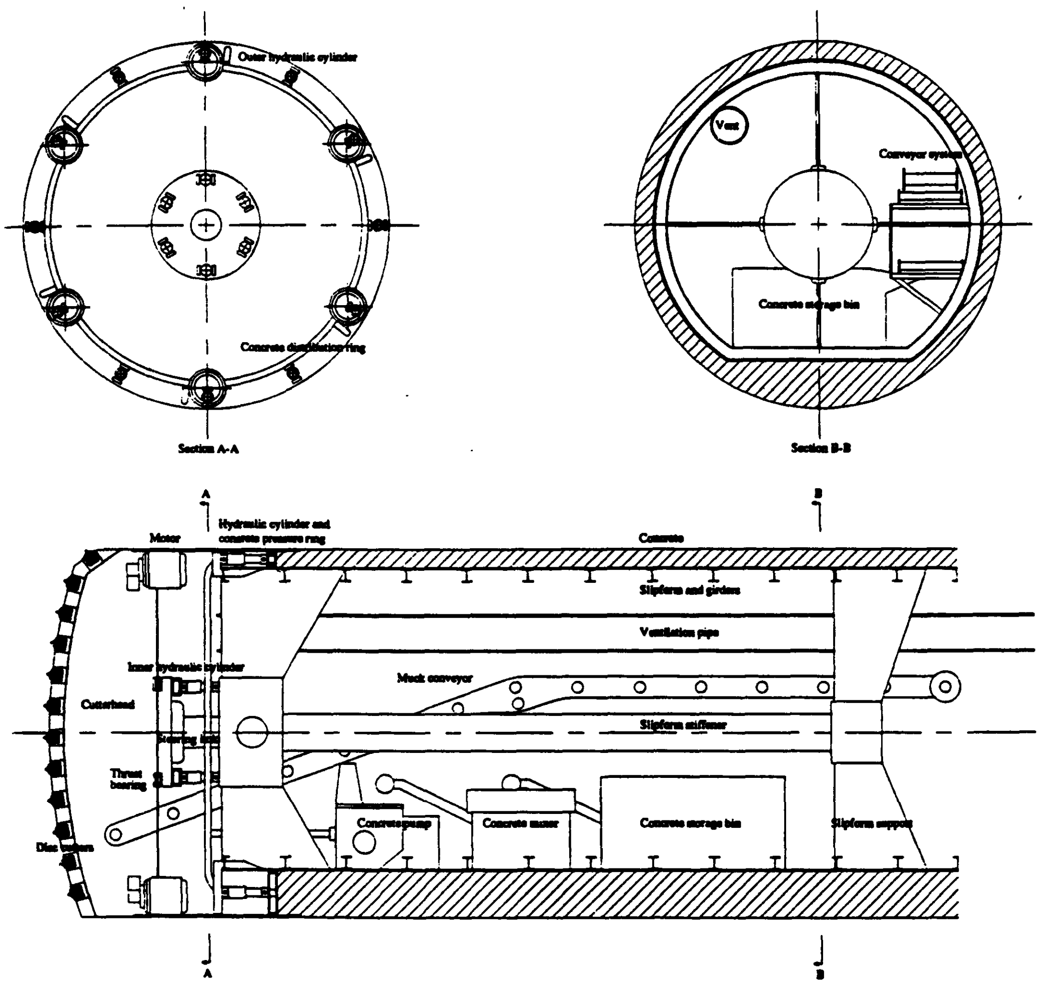


Figure 1-7: The conceptual design of CTBM in Marsh's thesis

stein in 1993 in MIT Civil Engineering Department. It covers the operations research on the CTBM and the force analysis of the ground-structure interaction for CTBM. This force analysis was done by both 2-D Finite Element analyses and closed-form elastic analyses developed by Einstein and Schwartz at MIT in 1979. The analysis is based at a model of 30 cm thick liner and 12 m long steel slipform under two simulating ground conditions: 10 m deep clay and 100 m deep dense sand.

1.2.3 Research done by Darrow

[3]

A thesis of "Design of a Continuous Tunnel Boring and Lining System" was done by Herbert Van Wyck Darrow directed by Professor Carl R. Peterson in 1993 in MIT Mechanical Engineering Department. It covers the design of the CTBM, including the boring system, material transport system, lining system, alignment control system, and some other support systems. The layout is shown in Figure 1-8.

In his research, the conceptual design of this CTBM is almost complete but two potential problems remained unsolved. One is the lip seal that may fail to keep the pumped concrete out of the cutter head, and the other one is the magnitude of the friction acting on the slipform from the concrete liner when substantial loads are applied by the earth on the liner.

1.2.4 Research done by Kelley

[7]

A thesis of "Concrete Lining System for the Continuous Tunnel Boring Machine" was done by Gail S. Kelley directed by Professor Herbert H. Einstein in 1995 in MIT Civil Engineering Department. It covers the knowledge of concrete and it does a wide range survey of different mixes of concrete to meet the need of the CTBM. It points out two important criteria of concrete for the CTBM liner: it needs a very high early strength and it has to be pumpable. Therefore it suggests the use of type III Portland cement (high early strength cement) and chemical admixture superplasticizer to meet

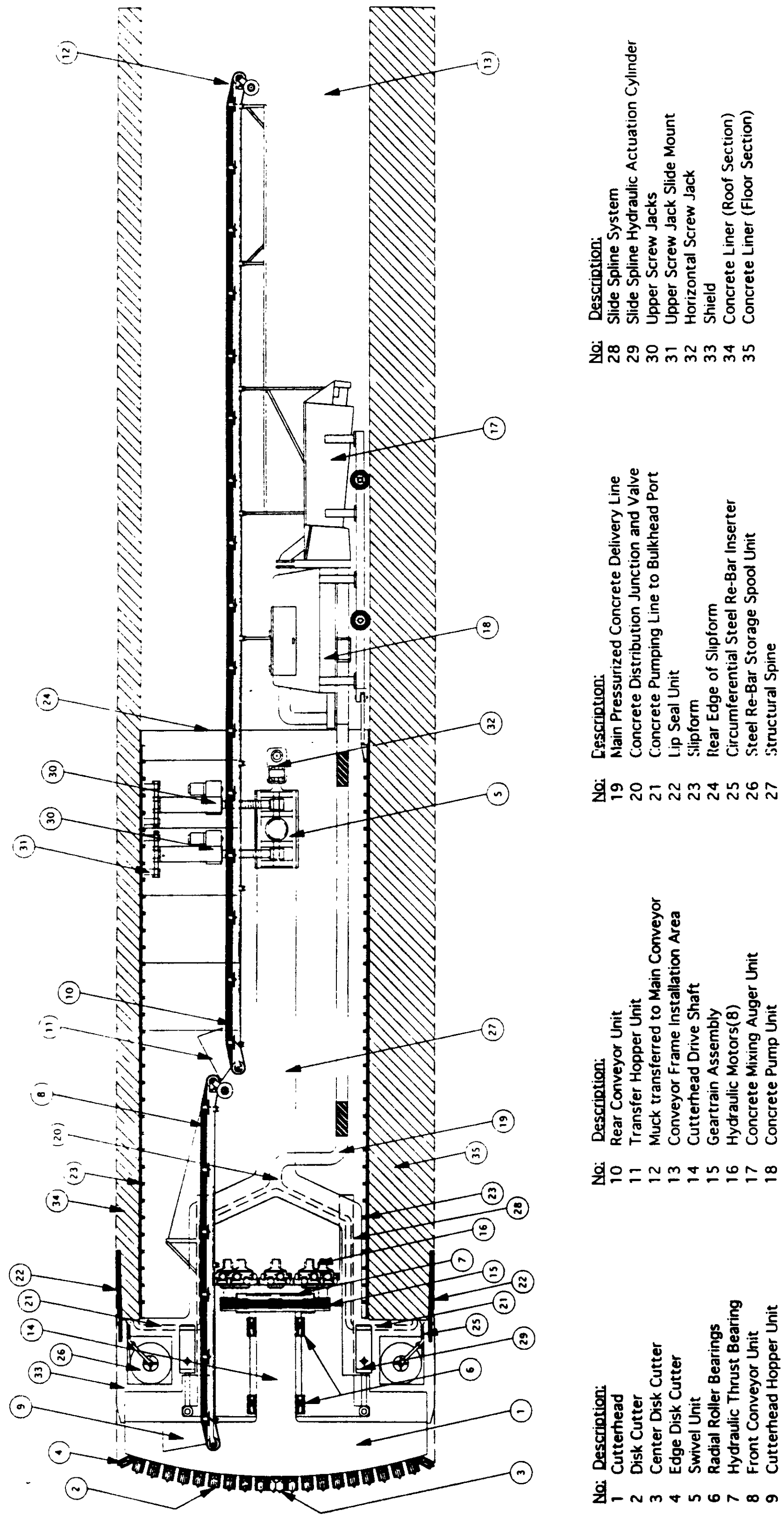


Figure 1-8: The conceptual design of a CTBM in Darrow's thesis

those requirements.

1.3 Objective of Research

In this research, a test apparatus is constructed to measure the friction acting on the slipform of the CTBM from the pumped concrete. The concept of CTBM is based on the research done by Marsh and Darrow, the simulation of the pressure from the ground-liner interface to the liner-slipform interface is based on Gupta's work, and the choosing of mix of concrete follows the suggestion by Kelley. A twenty foot long testing device is built to simulate the real forty foot long CTBM. Concrete is pumped into the device continuously analogous to the real machine, and it is compressed by hydraulic cylinders to simulate the pressure from the ground. A sixteen foot long strip of steel is used to simulate the slipform of the CTBM, and the strip is designed to be pulled out of the concrete by a motor at a speed of 0.5 in/min to 2 in/min, which is half the speed of the real CTBM. Thus the half-length simulator experiences the full concrete curing sequence. From the history of the drag force during the 2-5 hour test, the friction force between the slipform and the concrete in different hardened condition is determined, and the results can be used to polish the design of the CTBM.

Chapter 2

Background of the Experiments

2.1 The Design of the CTBM

The conceptual design of the CTBM can be found in Marsh's and Darrow's thesis. The drawings of the basic concept of the CTBM have been shown in chapter one. The force balance of the machine is shown in Figure 2-1.

The propulsive force from the pumped concrete is

P=p(pressure Of concrete) A(cross section area of concrete liner)

The cross section area of the concrete liner is shown in Figure 2-2.

The propulsive force has to conquer the drag force D acting on the machine, and it provides the excavating thrust F.

$$P - D = F$$

The propulsive force P and excavating thrust F can be predicted simply by

P = pA = 250psi × (Area)

= 1,907,700 lbs (For Tunnel With Minimum Wall)

= 3,525,265 lbs (For Tunnel With Maximum Wall)

(refer to Figure 2-2)

F_{total} = F(thrust per cutter)max × N(number Of cutters)

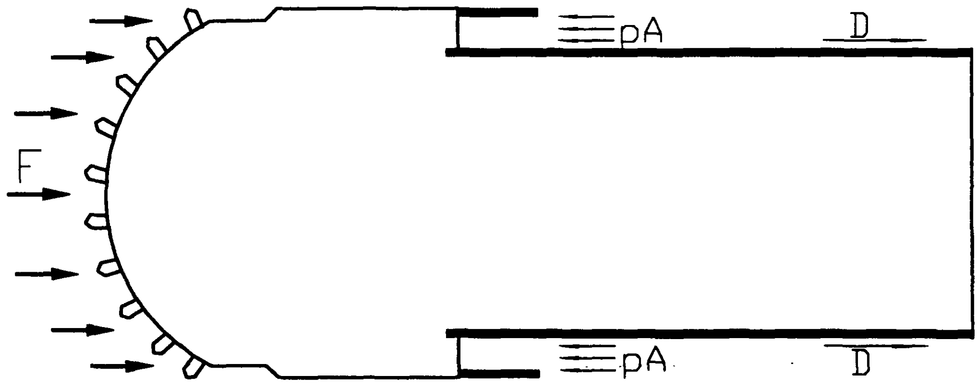


Figure 2-1: The force balance of a CTBM

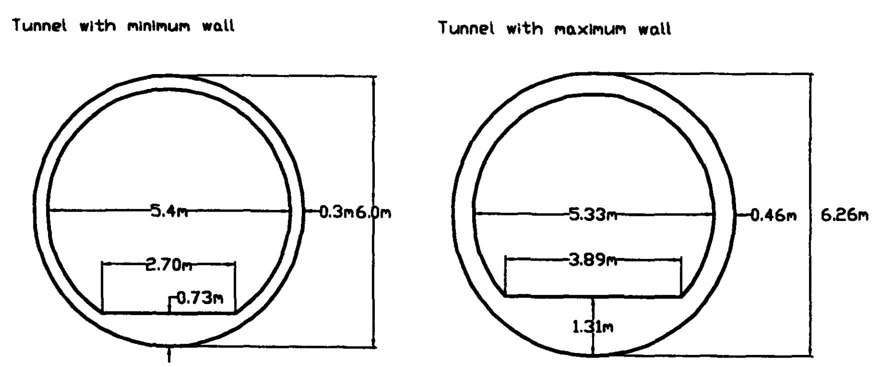


Figure 2-2: The cross area of the concrete liner of a CTBM for the 6 meter design

$$= 35 \, \frac{tons}{cutter} \times 40 \text{ cutters}$$
$$= 1{,}400 \text{ tons} = 2{,}800{,}000 \text{ lbs}$$

However, the drag force D is more complicated than these two forces. It is mostly from the friction acting on the slipform caused by the solid concrete under normal forces from the pressure of the ground, the torque transfer from the cutterhead, and the weight of the machine. It is partly from the pressure of the liquid concrete acting on the shield and lip seal, and the pull of the equipment, facilities and conveyor system. The prediction of the drag force will be discussed in next sections.

2.2 The Ground-Structure Interaction for CTBM

In order to calculate the friction acting on the slipform, we have to understand the performance of the interfaces between the ground and liner, and between liner and slipform. From Gupta's research, we can obtain the result by Finite Element Method. In Figure 2-3, normal stresses at the interfaces are shown.

- Clay model:
  normal stress = 0.15 M Pa from ground to concrete liner
  normal stress = 0.05 M Pa from concrete liner to slipform

- Dense sand model:
  normal stress = 1.50 M Pa from ground to concrete liner
  normal stress = 0.70 M Pa from concrete liner to slipform

2.3 Drag Force

The drag force should include

- drag force acting on the shield just behind the cutterhead

- drag force acting on the lip seal

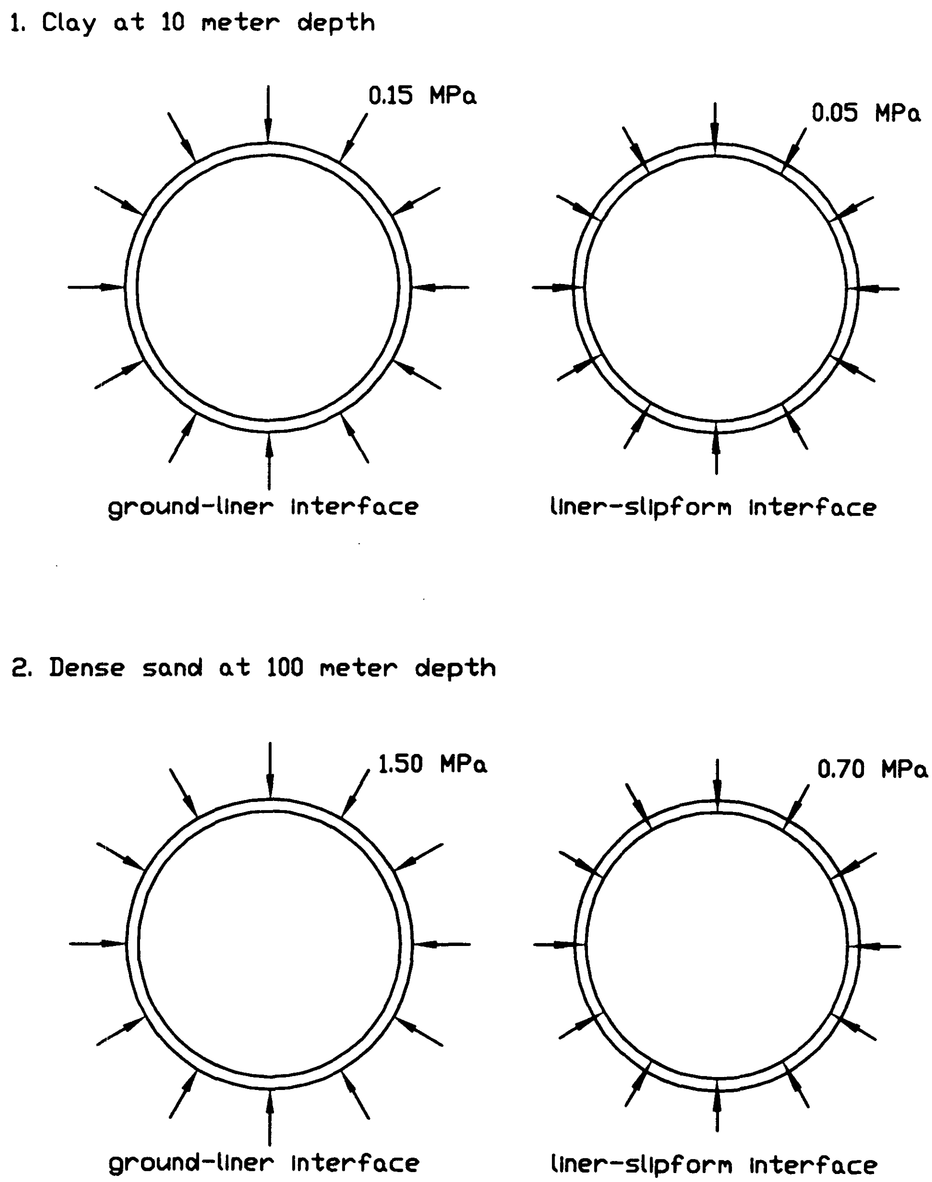


Figure 2-3: Result of FEM analysis on interfaces from ground to slipform

- drag force acting on the slipform due to ground pressure
- drag force acting on the slipform due to torque transfer contact pressure
- drag force of equipment towed behind the CTBM
- force required to extend the conveyor belt system

In the following sections, we will cover different approaches of the prediction and modeling of the performance of the drag force acting on the slipform.

2.3.1 Marsh's Approach

In his research, Marsh only considered the drag force caused by the weight of the machine. The rough estimation is based on the assumption that half the weight rests on the cutter head, and half on the slipform. Using the coefficients of friction of steel on rock ($\mu = 0.35$) and steel on concrete ($\mu = 0.40$), and an estimate of the weight of the machine (250 tons), the drag forces are:

$$f_{rock} = \frac{weight}{2} \times \mu_{steel/rock} = 430kN = 96,530lbs$$
$$f_{concrete} = \frac{weight}{2} \times \mu_{steel/rock} = 480kN = 108,000lbs$$

The model of the curing concrete in the slipform is a three region model as shown in Figure 2-4.

In region 1, the fresh concrete is liquid and can either be modeled as a Bingham fluid, or more simply be analyzed by using empirical data from concrete pump manufacturers for pressure drop in pipes. From the manufacturers' data, the pressure drop of the concrete in a pipeline is given by the following formula:

$$\Delta p = \frac{4\tau L}{D}$$

where

Δp = change in pressure

τ = flow resistance per unit internal surface area of pipe

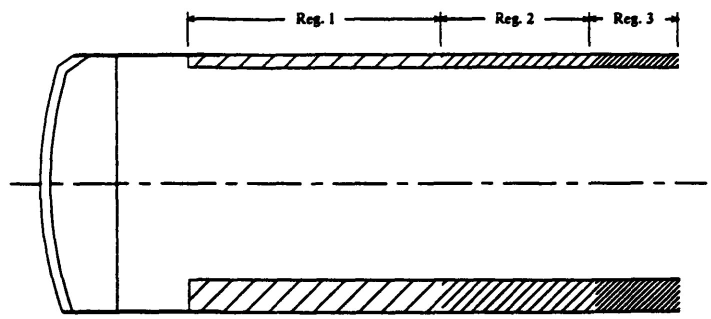


Figure 2-4: Three region model of curing concrete

L=length of pipe

D=internal diameter of the pipe

In the CTBM, we can use the data of τ to estimate the drag force by

$$Dragforce = \tau \times SurfaceArea$$

. The shear resistance τ is roughly 0.7 kPa from the data from Schwing and Putzmeister, two concrete pump manufacturers, so we can calculate the drag force on region one as roughly 90 kN or 20,000 lbs.

In region 2, the concrete has lost its initial slump, but has not yet set. However, the transition from fluid to set concrete is rapid so this region is about two meters long if the CTBM is advancing at six meters per hour. The drag force on the slipform is approximated as $pAtan\phi$, where p is the concrete pressure, A is the wetted area, and ϕ is the shear factor which is fairly low in this region ($\phi < 5^o$). If the pumping pressure of concrete is 1600 kPa (230psi), the drag force is estimated as 440 kN (99,000 lbs).

In region 3, the concrete has reached an initial set and is capable of supporting the ground loads imposed on it. The friction coefficient is assumed as $\mu = 0.4$, and

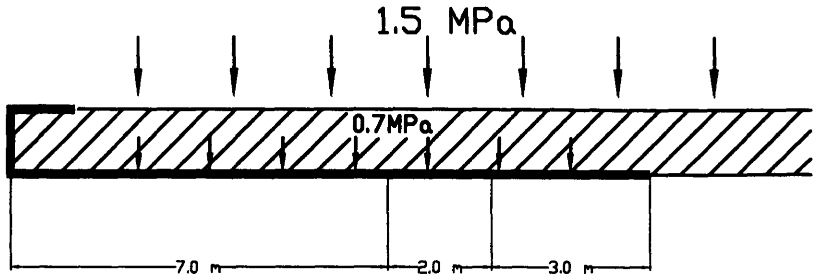


Figure 2-5: The model of Gupta's research

half of the weight is supported by this region as mentioned at the beginning, the drag force is approximately 480 kN (108,000 lbs).

2.3.2 Gupta's Approach

In his research, Gupta considered the ground-structure interaction, and found the relations between the interfaces of ground-liner and liner-slipform as shown in Section 2.2. His approach to estimate the friction on the slipform is by assuming the friction coefficients in all the regions are all the same as

$$f = tan25^o = 0.466$$

. From Figure 2-5, we can calculate the friction force on the slipform by a dense sand model in 100 m depth by

$D_{slipform} = 0.7 \times 10^6 (\frac{N}{m^2}) \times 12(m) \times Circumference(m) \times 0.466$

$D_{slipform} = 3.9 \times 10^6 (\frac{N}{m}) \times Peripheral(m)$

$D_{slipform} = 3.9 \times 10^6 \times 17(N)$

$D_{slipform} = 66300kN = 14,883,673lbs$

The drag force calculated by Gupta's research is 70 times larger than the pre-

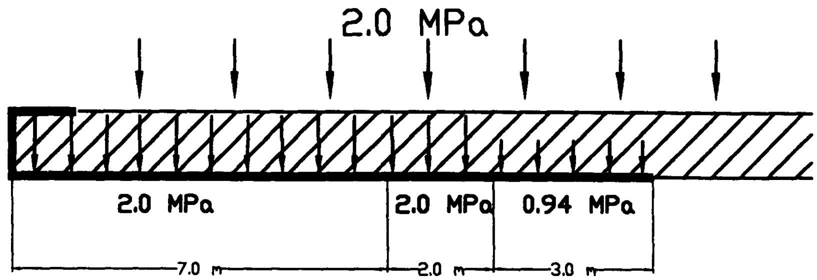


Figure 2-6: The model of Darrow's research

diction in Marsh's research. In Marsh's research, the pressure from the ground is neglected and it causes the failure of his model in soft ground. In Gupta's research, he overestimates the friction coefficient of the fresh concrete and it probably makes the model too conservative.

2.3.3 Darrow's Approach

Darrow's research covers a detailed calculation of the dynamic drag force acting on CTBM. His approach of estimating the friction on the slipform due to the ground pressure is based on a three region model as shown in Figure 2-6.

The drag force in region 1 due to shearing of the fresh concrete is given by:

$D_1 = \tau_1 A_1$

The drag force in region 2 due to ground pressure is given by:

$D_2 = \mu_2 P_2 A_2$

The drag force in region 3 due to ground pressure is given by:

$D_3 = \mu_3 P_3 A_3$

The drag force caused by half of the CTBM weight is given by:

$D_w = \mu_3 F_w$

The drag force caused by the torque transfer from the cutter head is given by:

Table 2.1: Drag forces acting on the slipform from Darrow

Liner	Thick Liner	Thin Liner	Thick Liner	Thin Liner
Ground	Clay at 10m	Clay at 10m	Sand at 100m	Sand at 100m
$\tau_1(lb/ft^2)$	58.48	58.48	58.48	58.48
μ_2	0.087	0.087	0.087	0.087
μ_3	0.3	0.3	0.3	0.3
P_1**(psi)**	30	30	300	300
P_2**(psi)**	30	30	300	300
P_3**(psi)**	6.6	9.9	93.0	141.0
$A_1(ft^2)$	1157.8	1197.7	1157.8	1197.7
$A_2(ft^2)$	347.4	359.3	347.4	359.3
$A_3(ft^2)$	520.03	538.95	520.03	538.95
D_1**(lbs)**	67,700	70,000	67,700	70,000
D_2**(lbs)**	140,700	145,500	1,407,000	1,350,000
D_3**(lbs)**	148,600	232,800	1,486,000	3,283,000
D_w**(lbs)**	75,000	75,000	75,000	75,000
D_{tt}**(lbs)**	81,230	81,230	81,230	81,230
D_{total}**(lbs)**	513,224	604,634	3,116,794	4,860,000

$D_{tt} = 2\mu_3 \frac{Torque}{d_{tt}}$

where

D=drag force acting on the slipform

τ_1=shear resistance of concrete in region 1

μ_i=coefficient of dynamic friction between slipform and liner in region 2 and 3

P_i=pressure carried by slipform in region 2 and 3

A_i=surface area of region i interface between slipform and liner

F_w=half weight of the CTBM=250,000 lbs

Torque=the torque from the cutting head = 1,184,615 ft-lbs

d_{tt}=offset of contact forces from the centerline of the slipform=8.75 ft

Considering the worst situation of the result, it is shown in Figure 2-6, regardless of the drag force caused by the torque transfer and the weight of the machine, the friction force acting on the slipform should be:

$D_{slipform} = \tau_1 A_1 + \mu_2 P_2 A_2 + \mu_3 P_3 A_3$

$D_{slipform} = 58.48(lbs/ft^2) \times 7(m) \times Circumference(m)$

Table 2.2: Drag forces acting on the CTBM from Darrow

Liner	Thick Liner	Thin Liner	Thick Liner	Thin Liner
Ground	Caly at 10m	Clay at 10m	Sand at 100m	Sand at 100m
Drag on shield (lbs)	208,164	202,591	1,406,640	1,350,912
Drag on lip seal (lbs)	58,015	55,584	537,405	514,912
Drag on slipform (lbs)	513,224	604,634	3,116,794	4,859,516
D from equipment (lbs)	5,000	5,000	5,000	5,000
D from conveyor (lbs)	28,103	28,103	28,103	28103
Total drag force (lbs)	812,506	895,912	5,093,942	6,295,023

$$+0.073 \times 300(psi) \times 2(m) \times Circumference(m)$$

$$+0.3 \times 141(psi) \times 3(m) \times Circumference(m)$$

$$D_{slipform} = 2804(N/m^2) \times 7(m) \times Circumference(m)$$

$$+0.073 \times 2.0(Mpa) \times 2(m) \times Circumference(m)$$

$$+0.3 \times 0.94(MPa) \times 3(m) \times Circumference(m)$$

$$D_{slipform} = 1.21 \times 10^6 \times Circumference(N)$$

$$D_{slipform} = 1.21 \times 10^6 \times 17(N)$$

$$D_{slipform} = 20,570kN = 4,618,000lbs$$

Some errors were found because of the transfer of metric units and English units. However, we obtained the typical value of the friction here, which is about 4,500,000 lbs to 5,000,000 lbs from Darrow's approach. It is about 30 % the value of Gupta's estimation. Furthermore, the shear resistance of the fresh concrete τ is $58.48lb/ft^2$ (or 0.4 psi), which is 4 times the value in Marsh's research ($\tau = 0.7kPa = 0.1psi$).

Furthermore, in Darrow's research, he not only calculate the drag force due to the friction on the slipform, it also covers the drag force from other factors, which are shown in Table 2.2. Still, the drag force acting on the slipform is the main part of the total drag force from the result of his research.

Chapter 3

Design of the Experimental Apparatus

3.1 Schematic Design

The experimental apparatus is built to simulate the CTBM in advancing, designed to measure the friction acting on the slipform due to the ground pressure as the concrete progressively cures. The schematic design of this apparatus is shown in Figure 3-1. It has the following features:

- It simulates of the pressure from the ground, up to 300 psi based on the dense sand model at 100 m depth
- It pumps the concrete continuously with pumping pressure up to 100 psi, compared to 250 psi applied in the real machine. (Concrete pressure is not the propelling mechanism in the simulation.)
- It is 6 meters long, half the length of the CTBM. Because of this scale, the machine runs at half the speed of the CTBM, which is 2 in/min.
- One inch wide steel strip is used to simulate the slipform of the CTBM
- Concrete is pumped at cross area $1in^2$ at 100 psi at most, the propulsive force from concrete will be 100 lbs at most.

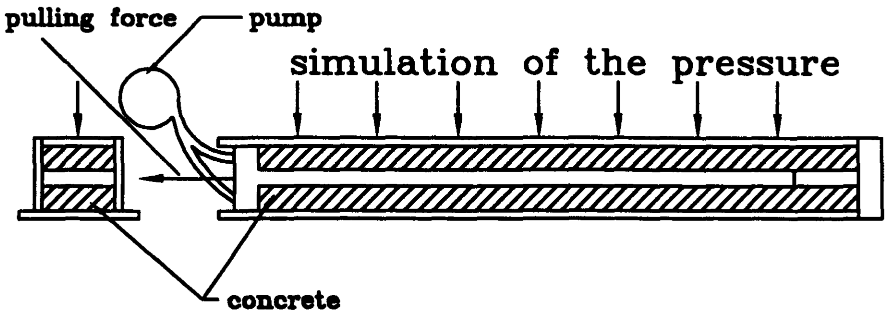


Figure 3-1: Schematic design of the experimental apparatus

- Concrete is pumped into both sides of the steel strip, so the steel strip can be kept in place without other bearings that might cause additional drag force.
- Most parts of the apparatus are made by steel because of the high load applied on the machine.
- Propulsive force to advance the steel strip is provided separately and measured by a load cell.

3.1.1 Estimated Friction

From last chapter, we obtain the equation to estimate the friction acting on the slipform from the researches done by Darrow:

From Darrow's approach (three region model):

$D_{slipform} = \tau_1 A_1 + \mu_2 P_2 A_2 + \mu_3 P_3 A_3$

$D_{slipform} = 2804(N/m^2) \times 7(m) \times Circumference(m)$

$+0.073 \times 2.0(MPa) \times 2(m) \times Circumference(m)$

$+0.3 \times 0.94(MPa) \times 3(m) \times Circumference(m)$

$D_{slipform} = 1.21 \times 10^6 \times Circumference(N)$

The length of the experimental apparatus is half the size of the CTBM, and the "Circumference" here is two inches long (both sides of the one inch strip). Therefore, we can estimate the performance of this testing device:

$D_{slipform} = 1.21 \times 10^6 \times \frac{2.54}{100}(N)$

$D_{slipform} = 30,734(N) = 6,900(lbs)$

3.1.2 Estimated Size of Pulling System

From this data, for a hot rolled steel with yielding strength $\sigma_y = 50kpsi$ with safety factor 2, we'll need a steel strip, pulling pins, and other relative parts all with cross section areas $0.28in^2$. To save the space and the size of the testing device, we decide to use 2,000lbs as our rated force by running the machine for 1/4 length (5ft) under full pressure or for full length (20ft) under 1/4 the full pressure from the ground. The objective is to determine the frictin coefficient, not the maximum friction force.

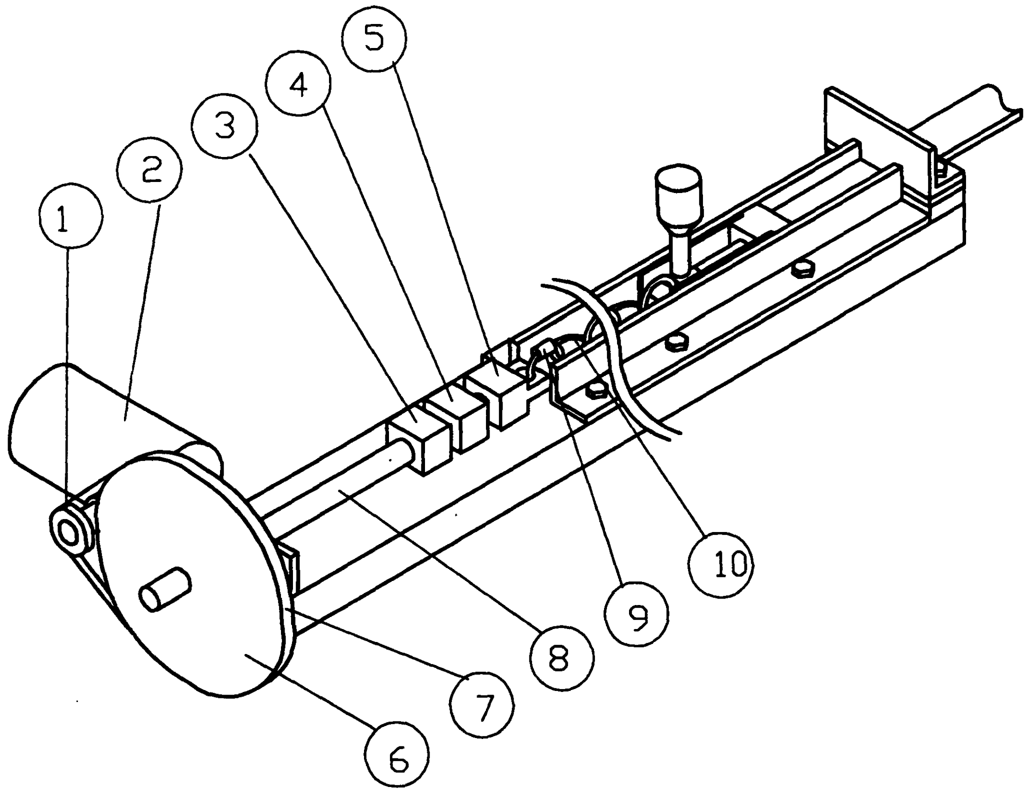
3.1.3 Estimated Size of Hydraulic Cylinders and Accesories

The simulation of the pressure from the ground will be accomplished by hydraulic cylinders spaced 16 inches apart. Each hydraulic cylinder will apply pressure to an area of $16in^2$. Since the pressure is up to 300psi, the load of the hydraulic cylinders should be rated 4,800lbs. We chose the hydraulic cylinders with rated load 5tons under the pressure of 10,000psi from the hydraulic pump. To withstand the high hydraulic pressure, 3/8" schedule 80 seamless pipes are specifically chosen for this usage. Similarly, the structure to support the hydraulic cylinders should be strong enough to withstand 4,800lbs.

In the following sections, we will cover the conceptual design of the driving system, concrete pumping system, ground pressure simulating system, and data acquisition system. The detail design drawings, including assembly drawings and part drawings, are shown in Appendix A and B.

3.2 Conceptual Design

3.2.1 Driving System



1. driving sprocket 8 teeth
2. motor with speed controller
3. pull block
4. load cell rated 2000 lbs
5. chain pull
6. driven sprocket 80 teeth
7. ladder chain made by high tensile steel, rated 130 lbs
8. pull screw 3/4-10
9. chain hook
10. chain

Figure 3-2: Conceptual design of the driving system

Table 3.1: Specifications of the driving motor

Motor	Input V	Input Amp	RPM	HP
	115V DC	1.43	1725	1/8
Recuder	Torque	RPM	Ratio	
	32.0 in-lbs	173	10:1	
Controller	Input V	Max. Amp	Output V	Output Amp
	115V AC	3	0-125V DC	0.7

The conceptual design of the driving system is shown in Figure 3-2. It includes a DC motor(2), a pair of sprockets and a ladder chain(1,6,7), a screw rod(8), a pull block(3), a load cell rated 2,000lbs(4), a chain pull(5), and chains(9,10).

Choosing The Motor

The motor is a shunt DC motor with 1/8 horsepower. It is chosen by the power output:

$Power_{needed} = Force \times Velocity = 2000(lbs) \times 2(in/min)$

$Power_{needed} = 4000(in - lbs/min) = 0.01hp$

It is reasonable to choose a motor with power that is 12 times the power needed for the device because the motor output will be processed to three reduction steps, and it will cause a lot of loss of power. The specifications of the motor is shown in Table 3.1. From the table, we can find that the controller reduces the input current to half the rated input current, thus the power output of the motor has already been reduced to 1/16 hp, 6 times the power needed for the device. Furthermore, the reduction gears built in has reduced the rated power output to:

$Power_{AfterReducer} = \tau(Torque) \times \omega(AngularSpeed) = 32.0(in/lb) \times 173(rpm)$

$Power_{AfterReducer} = 48.3(ft - lbs/sec) = 0.088hp = 70\% Power_{motor}$

It means the power has already been reduced to about 4 times the power needed to run the machine after the controller and the built in speed reducer.

Designing the Speed Reducer

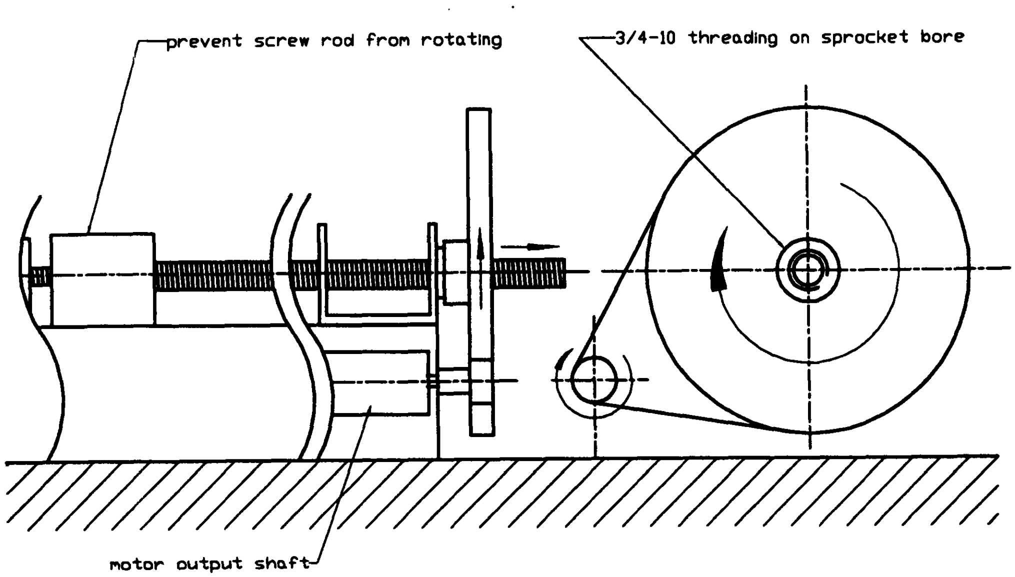


Figure 3-3: Conceptual design of the speed reducer

The speed needed for the device is up to 2 in/min, and the speed of the motor after the built in reducer is rated 173 rpm at torque 32.0 in-lb. The conceptual design of the reducer is shown in Figure 3-3. The speed is reduced by a pair of sprockets of ratio 10:1, and then be reduced again by a screw rod of pitch 1/10. Therefore, the screw rod can be driven by 2 in/min, the driven sprocket (80 teeth) should rotate at 20 rpm, and motor output shaft should rotate at 200 rpm. It is acceptable since we has chosen a shunt motor with extra power output, it will still provide enough torque at higher speed than the rated speed. Usually the efficiency of a flexible driving system is about 80%, and of a power screw system is about 35 % because of the friction. Therefore, the total efficiency of the speed reducing system is about

$$\eta_{reducer} = \eta_{chain}\eta_{screw} = 0.8 \times 0.35 = 0.3$$

That means the power from the motor has been reduced to 1.2 times the power needed after all of the power transmission.

The motor is fixed on a wood base with slots which allow the motor to move forward and backward for the adjustment of the ladder chain.

The choosing of a pair of sprockets rather than a pair of reduction gears is because:

- It is easier to do adjustment on the ladder chain by streching it tight, it is more difficult to adjust gears to a precise position at which there is no noise when operating.
- It doesn't need lubrication on the ladder chain when running at low speed.
- The force on the ladder chain is about 64 lbs only, and the ladder chain can afford it (rated 130 lbs).

The driven sprocket is tapped with 3/4-10 threading in it's bore which is 13/16" long. The driven sprocket works like a nut to drive the screw rod forward. Besides, a pull block is added at the end of the screw rod to prevent the screw rod from rotating as shown in Figure 3-3. The screw rod is chosen because:

- It is easy to build the power screw system by just cutting a screw rod, drilling a pilot hole on the sprocket and tap it, althought the efficiency is low to 35%.
- It saves more space than a gear-rack system or linkage system.
- It is easy to reset the screw rod.

The stress analysis is shown in Appendix C. The force calculation of the power screw system is based on the pulling force of 2,000 lbs. The analysis includes the average shear stress on the screw rod τ_1, the average shear stress on the nut (driven sprocket) τ_2, and the average bearing stress on the screw σ. The results are:

$\tau_1 = 2500psi$

$\tau_2 = 2100psi$

$\sigma = 1850psi$

The stress analysis proves that the screw rod of 3/4-10 is very safe for the usage of the load of 2000lbs. Assume the yielding strength is 60kpsi, the safty factor is almost 20.

The torque analysis is shown in Appendix C. The torque T needed to drive a load by a screw rod is

$T_{ideal} = 32in - lbs$

$T_{real} = 95in - lbs$

efficiency $\eta = \frac{T_{ideal}}{T_{real}} = 32/95 = 34\%(\mu = 0.08)$

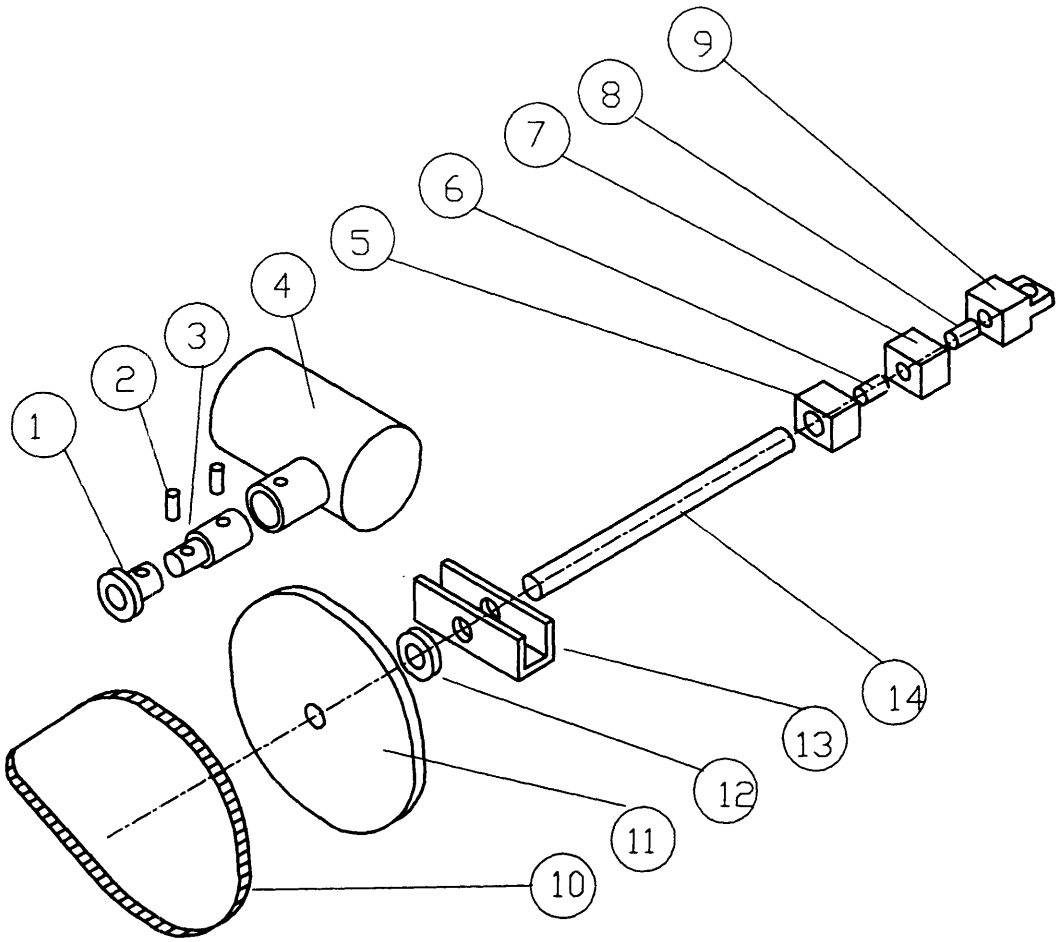
From Figure 3-4, we can understand the assembly of the driving system. The power is transmitted from the motor shaft to the driving sprocket (8 teeth) by a shaft connector with two set screws, then be transmitted by the ladder chain the the driven sprocket (80 teeth) with efficiency 80%, then be transmitted to the screw rod with efficiency 35%, and then the force pulled the load cell as well as the chain puller. The power supply starts at 0.0625hp after the controller and end by 0.012hp, the efficiency of the mechanical transmission from the built in reduction gears to the srocket pairs to the power screw is only 20%.

3.2.2 Concrete Pumping System

The conceptual design of the concrete pumping system is shown in Figure 3-5. It includes a simple pressure regulator, concrete container and pipes, and the head that combines the functions of pulling the slipform and pumping the concrete. Note that this system is intended only to deliver concrete to the test chamber as the chamber is lengthened by a separate chain pull system.

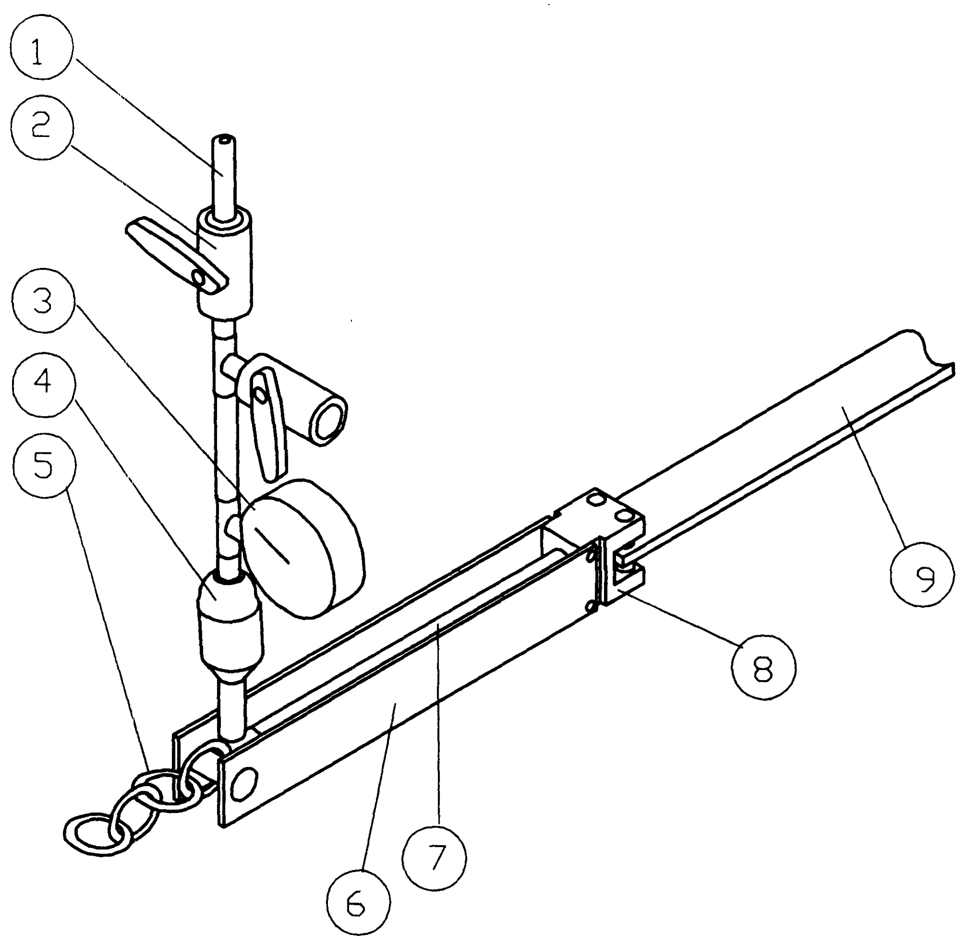
Air Pressure Regulator

The air pressure regulator is designed to provide the different pressures on different mixes of concrete because too much pressure will cause too much leakage of the concrete in the device, and too little pressure might not pump the concrete out of the container. Two important parts in the air pressure regulating system are the two valves which control the flow of the compressed air. The operating methods are shown in Figure 3-6.



1. driving sprocket 8 teeth
2. set screw
3. shaft
4. motor with speed controller
5. pull block
6. connecting screw 1/4-20
7. load cell rated 2000 lbs
8. connecting screw 1/4-20
9. chain pull
10. ladder chain made by high tensile steel, rated 130 lbs
11. driven sprocket 80 teeth
12. thrust bearing
13. support channel
14. pull screw rod 3/4-10

Figure 3-4: Explode view of the driving system



1. connector to compressed air source
2. valve
3. pressure gauge rated up to 100 psi
4. concrete container
5. chain
6. pull plate
7. pipe for pumping concrete
8. head
9. slipform

Figure 3-5: Conceptual design of the concrete pumping system

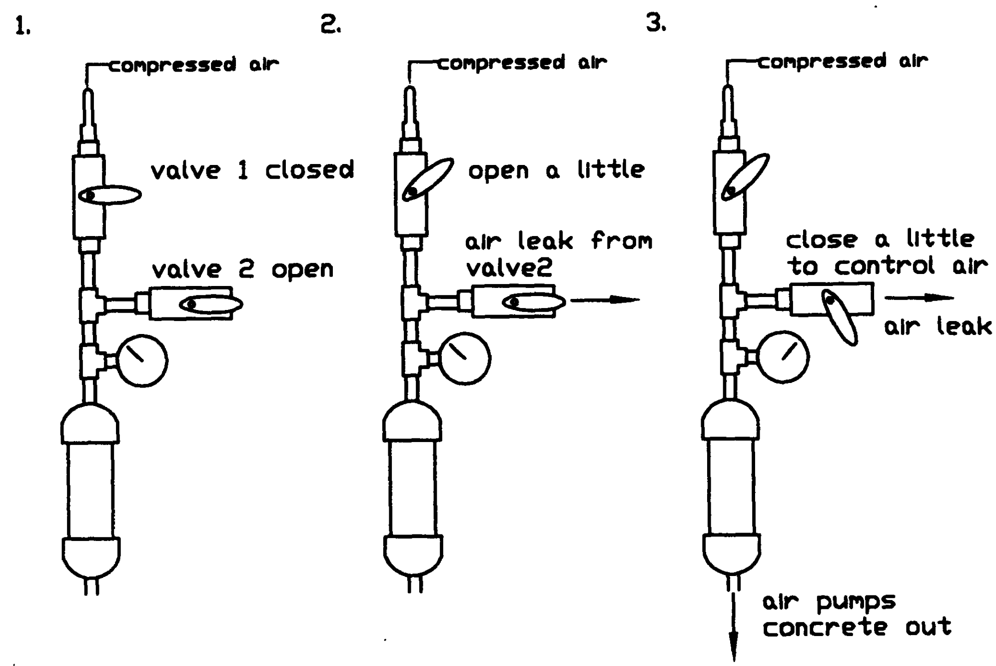


Figure 3-6: Conceptual design of the air pressure regulator

1. At first, the system is connected to the compressed air source at 100psi. Valve 1 is closed so the compressed air cannot pump the concrete out.

2. Open valve 1 a little bit with valve 2 open, allow air to leak from air source through valve2.

3. Close valve 2 slowly and stop when the pressure we need to pump out the concrete is reached.

4. If the pressure is too low when valve 2 is closed thoroughly, open valve 2 and start from step 2 again, and open valve 1 more to allow more air from air source to valve 2.

As shown in Figure 3-7, when we want to stop the air pressure on the concrete, we can follow the following steps to assure the safety:

1. Close valve 1 to stop the compressed air from going into the container.

2. Open valve 2 to release the compressed air trapped in the container.

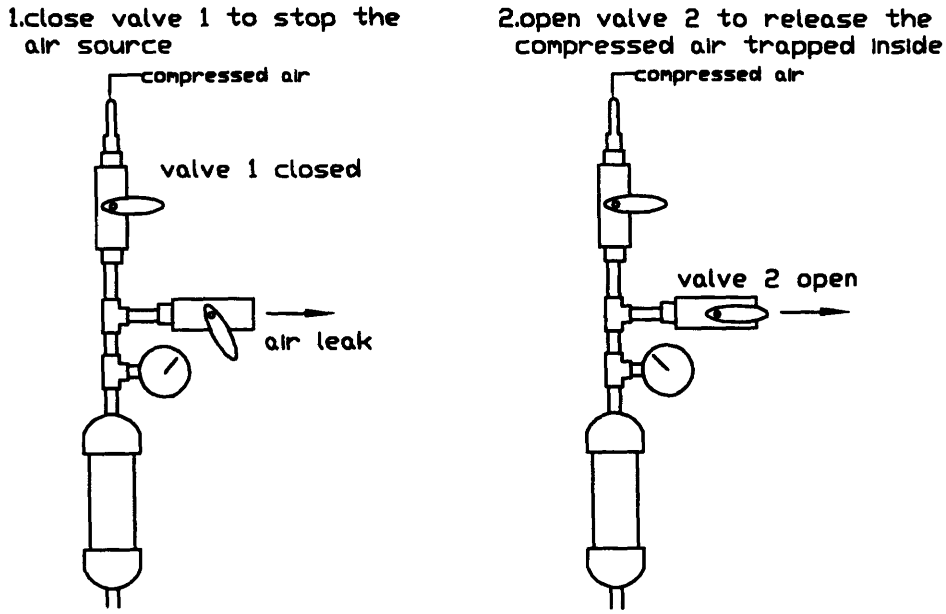


Figure 3-7: Stop the air pressure regulator

Pressure Drop of Concrete in Pipes

In chapter 2, we have discussed the shear resistance of a fresh concrete and obtain a formula to estimate the pressure drop due to the shear resistance from concrete pump manufacturers:

$$\Delta p = \frac{4\tau L}{D}$$

where

Δp = change in pressure

τ = flow resistance per unit internal surface area of pipe=0.7kPa

L=length of pipe

D=internal diameter of the pipe

In our testing device, we have 2 sections of pipes:

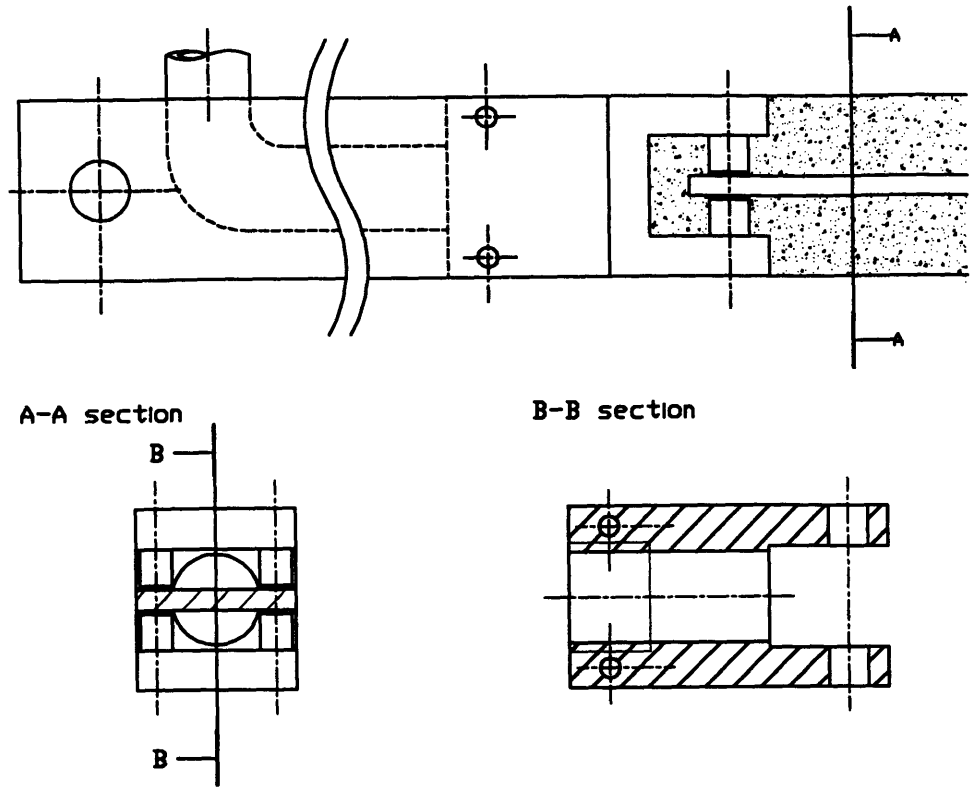


Figure 3-8: Design of the head of concrete inlet

- concrete container (D=2in, L=8in), pressure drop = 11.2kPa = 1.6psi
- pumping pipe (D=3/8in, L=25in), pressure drop = 187kPa = 27psi

Design of the Head of Concrete Inlet

Figure 3-8 is the detail design of the head of concrete inlet. It inludes the following funcitons:

- transmitting the force from the chain to pull the steel strip
- connect with the concrete pumping pipe
- wide open to prevent concrete from clogging inside
- seal the edge to prevent the concrete from flowing forward
- with cross section area only 1"x1.125"

The design challenge here is the combination of those functions with the limited size of the head. Concrete usually plugs whenever the cross section area is too small or there is a sudden cross section area reduction. To prevent the clogging, a 9/16" hole was drilled through the head, and the end of the head is milled open to increase the cross section area, and the remaining material is left for the transmission of the 2000 lbs force from the chain to the slipform. The slipform is fixed in place with the pins by C-rings rather than by bushings to increase the space for concrete to flow through. In this case, we risk bending stress in the pins.

Choosing the pins

From Figure 3-9, we can see the assembly of the concrete pumping system. Also, we can see how the 2000 lbs force is transmitted from the chain, to the 3/8" pin, to two plates designed to accommodate the central concrete pumping pipe, to two 1/8" pins, to the head, to two 1/4" pins, and then finally to the slipform. Because of the size limit, all the parts are designed carefully to prevent failure of the material. Since the material is ductile, and the load is static, we do not need to consider fatigue and force concentration.

For the 3/8" pin which is made of cold drawn steel ($\sigma_{yield} = 60kpsi$), we should consider shear stress and bending stress as well. For the pulling plate made of cold drawn steel, we should consider tension stress and bearing stress as well. The calculation is shown in Appendix C, and the results are:

For the 3/8" pin:

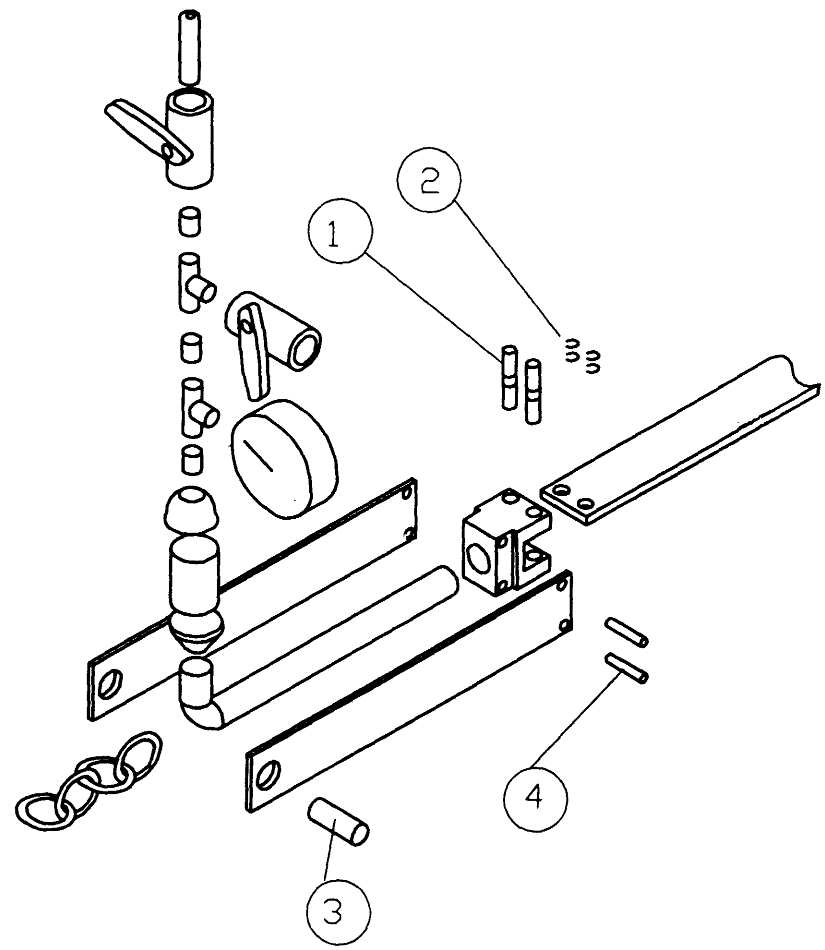
$\tau_{shear} = 9090psi$

$\sigma_{bending} = 36300psi$

$\sigma_{combined} = \sqrt{36300^2 + 3 \times 9090^2} = 40000psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{combined}} = 1.5$

For the pulling plate connectted with the 3/8" pin:



1. 1/4 pins
2. 1/4 C rings
3. 3/8 pins
4. 1/8 pins

Figure 3-9: Explode view of the concrete pumping system

$\sigma_{tension} = 10,600psi$

$\sigma_{bearing} = 21,300psi$

$N_{safety} = \frac{sigma_{yield}}{\sigma_{max}} = \frac{60000}{21300} = 2.8$

Choosing the 1/8" Pin For the 1/8" spring pins, we can use the rated shear load from the catalog since there is no bending stress in these parts. The rated load for spring pins 1/8" is 633 kgw (1400 lbs) [5]. For the pulling plate made of cold drawn steel, we should consider shear stress and bearing stress as well. The calculation is shown in Appendix C, and the results are:

For the 1/8" spring pins:

$$N_{safety} = \frac{RatedLoad}{RealLoad} = \frac{1400lbs}{500lbs/pin} = 2.8$$

For the pulling plate connectted with the 1/8" pin:

$\sigma_{tension} = 4,000psi$

$\sigma_{bearing} = 32,000psi$

$N_{safety} = \frac{sigma_{yield}}{\sigma_{max}} = \frac{60000}{32000} = 1.9$

Choosing the 1/4" Pin For the 1/4" pins which are made of cold drawn steel ($\sigma_{yield} = 60kpsi$), we should consider the shear stress and the bending stress as well. For the slipform which is made by hot rolled steel ($\sigma_{yield} = 50kpsi$), we should consider the tension stress and bearing stress as well. The calculation is shown in Appendix C, and the results are:

For the 1/4" pins

$\tau_{shear} = 10200psi$

$\sigma_{bending} = 40700psi$

$\sigma_{combined} = \sqrt{40700^2 + 3 \times 10200^2} = 44400psi$

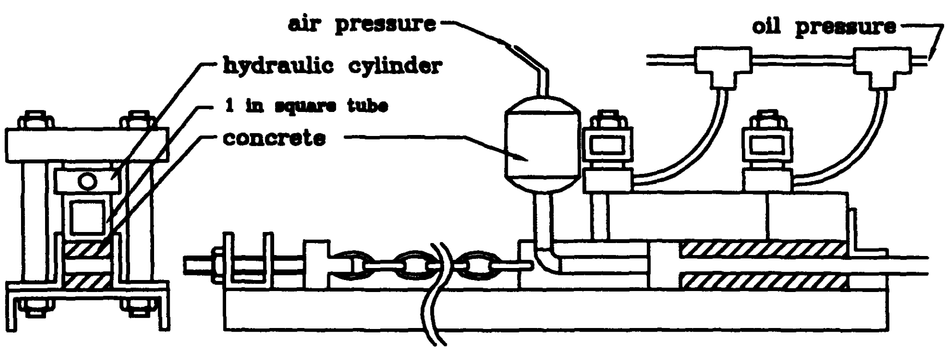


Figure 3-10: Conceptual design of the ground pressure simulating system

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{combined}} = 1.35$

For the slipform connectted with the 1/4" pin:

$\sigma_{tension} = 32,000psi$

$\sigma_{bearing} = 32,000psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{max}} = \frac{60000}{32000} = 1.9$

3.2.3 Ground Pressure Simulating System

The conceptual design of the ground pressure simulating system is shown in Figure 3-10. The pressure is provided by the hydraulic cylinders rated up to 5 tons. In the test, the force up to 2.4 tons will be applied from the hydraulic cylinders to 16 inch long by 1" square tubes to generate a uniform pressure up to 300 psi on the concrete. The hydaulic pressure needed will be 4800 psi, and it will be generated by a manual hydraulic pump rated up to 10,000psi, and the transmission pipes of the high pressure fluid are 3/8" schedule 80 seamless pipes.

From Figure 3-11 we can understand how the hydraulic cylinders apply forces on the concrete. The first drawing in Fig 3-11 shows the testing device without the appearance of the pressure simulating system. The second drawing shows how the hydraulic cylinders be located in place. The hydraulic cylinders start to apply pressure after the head of the concrete inlet leaves the section (actually after the head leaves three sections away from the location). When the hydraulic cylinder starts to apply pressure on the concrete, the structure shown in the second drawing backs the hydrualic cylinder by two 3/4-10 screw rods and one top beam. The hydraulic cylinder tries to extend out and presses on the 1" square pipe, and which generates a pressure on the concrete.

As shown in Section 3.2.1, the screw rod used under a load of 2,000 lbs has a safety factor of almost 20. The choosing of the size of the screw rods is actually very conservative and doesn't need more serious consideration. However, the bending of the top beam and the pressure press should be taken into consideration. The material of the 1" square tube is structural steel pipes with yield strength 70kpsi from catalog. The stress analysis of the top beam and the pressure press is shown in Appendix C, and the results are:

For the top beam:

$\tau_{shear} = 5500psi$

$\sigma_{bending} = 2200psi$

$\sigma_{combined} = \sqrt{2200^2 + 3 \times 5500^2} = 9800psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{combined}} = 5.1$

For the pressure press:

$\tau_{shear} = 5500psi$

$\sigma_{bending} = 64000psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{max}} = 1.1$

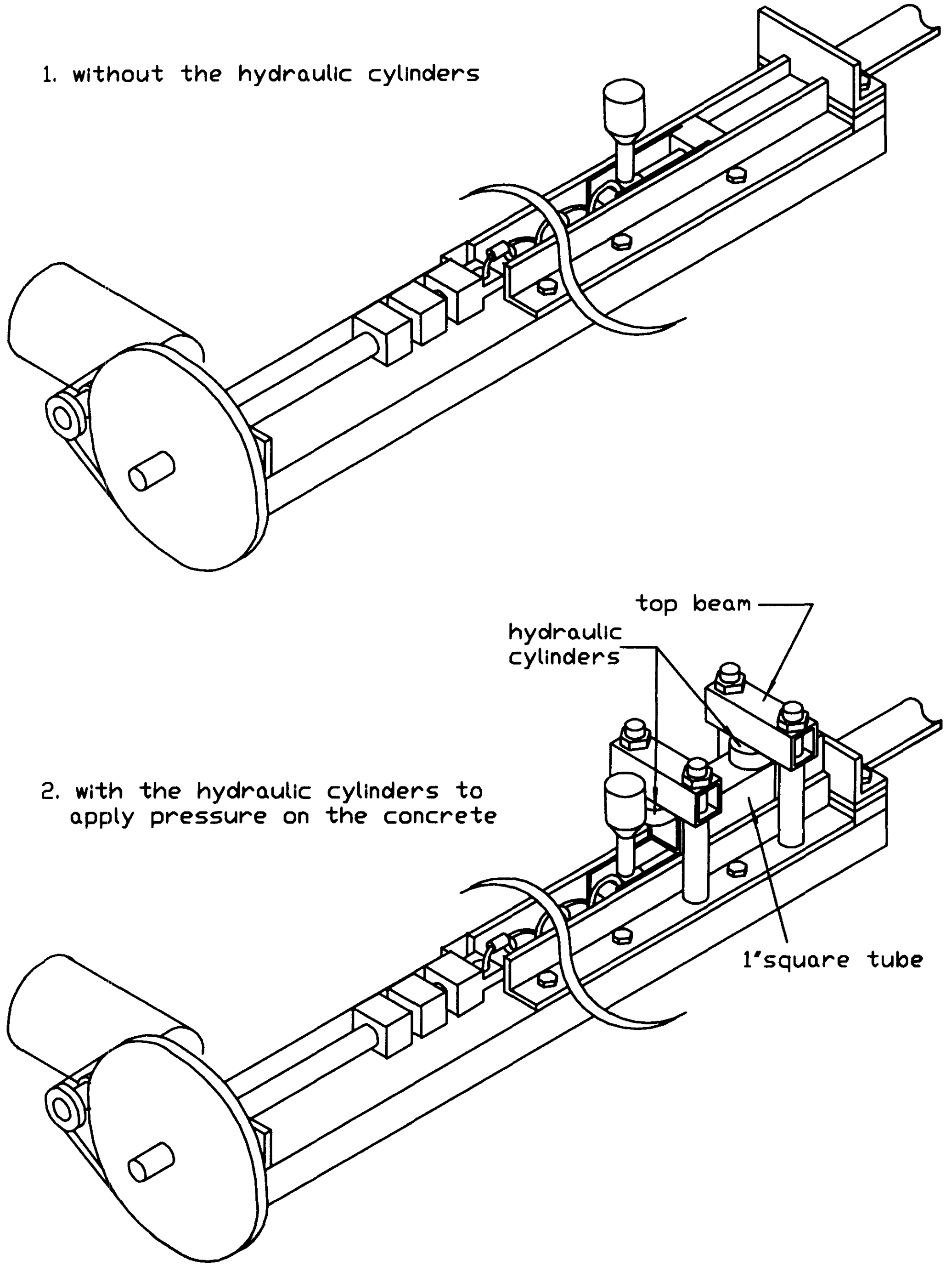


Figure 3-11: Assembly of the ground pressure simulating system

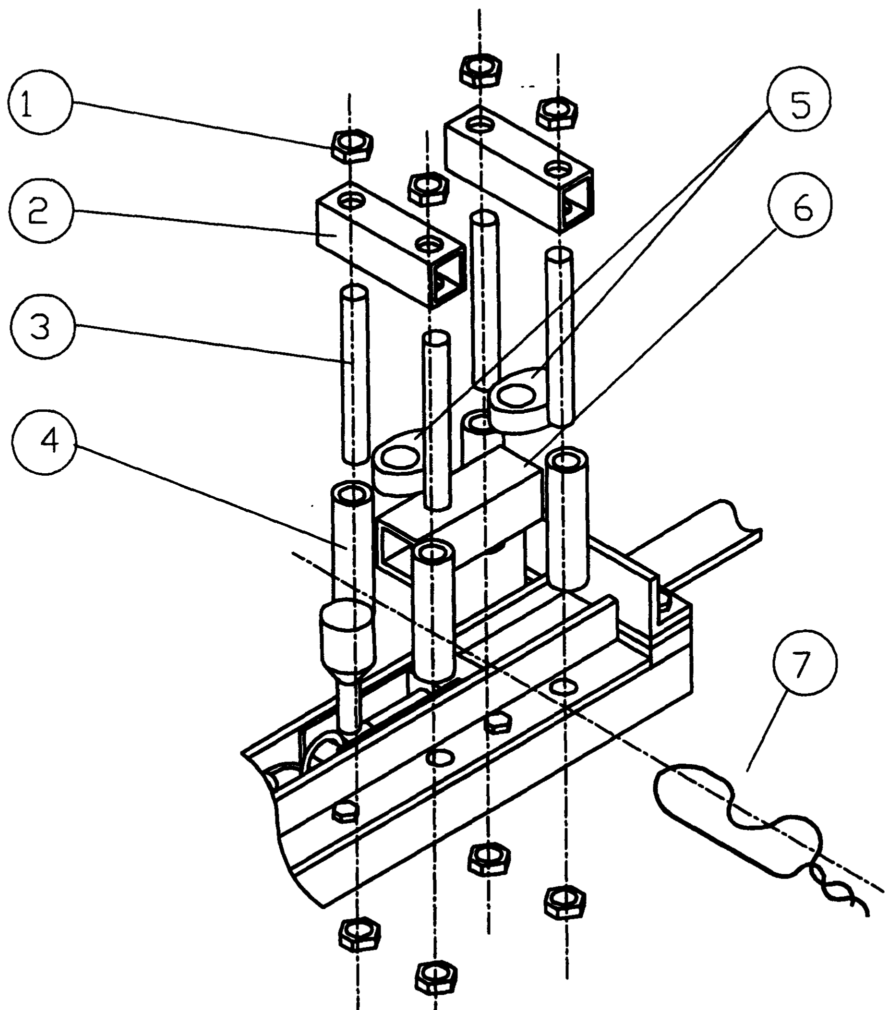
From the result, we know the design of the top beams and the supporting screw rods are oversized, but the pressure press has only safety factor of 1.1 which is too low. However, in the tests, the pressure presses worked well and did not yield. Actually the pressure is not uniform on the concrete. Bending of the steel tube reduces pressure from the concrete in the center of the span, concentrating it near the ends.

From Figure 3-12 we can have a clear idea of how the ground pressure simulating system is assembled. The structure to support the force from the hydraulic cylinders is mainly the threaded rods(3) with nuts(1) and the top beams(2), which are designed oversized. The pressure press(6) is located on top of the pumped concrete to spread the pressure on it. The hydraulic cylinders(5) go in between the structure and the pressure press.

The column covers(4) accommodate the screw rods inside, the purposes of those column covers are

- to keep the top beams in correct position vertically
- and to work as a stopper to stop the pressure press from moving forward when the machine is running by winding a wire (7) on both column covers and stop the pressure press from moving forward.

The holes drilled on the 20 feet long steel base and the steel angles are bigger than 3/4", the size of the screw rod. The purpose of the bigger holes is to allow a little space for the lateral adjustment of the steel angles which form a channel for concrete. If the space in between the steel angles is exactly 1.00" wide, there might be friction between the slipform(i.e., steel test strip) and the angles, or between the head and the angles. If the space is too much larger than 1.0", there will be excessive leakage of concrete from the clearance between the pressure press and the steel angles, and around the head of the concrete inlet. Also, there will be unpredictable friction between the concrete and the edges of the slipform under unknown pressure. Therefore, the steel angles are designed to be adjustable to make tradeoff between these two extreme situations.



1. 3/4-10 nut
2. top beam 1' square pipe
3. column 3/4-10 threaded rod
4. column cover 3/4 schedule 40 pipe
5. hydraulic cylinder rated 5 tons at 10,000 psi
6. pressure press 1' square pipe
7. wire

Figure 3-12: Explode view of the ground pressure simulating system

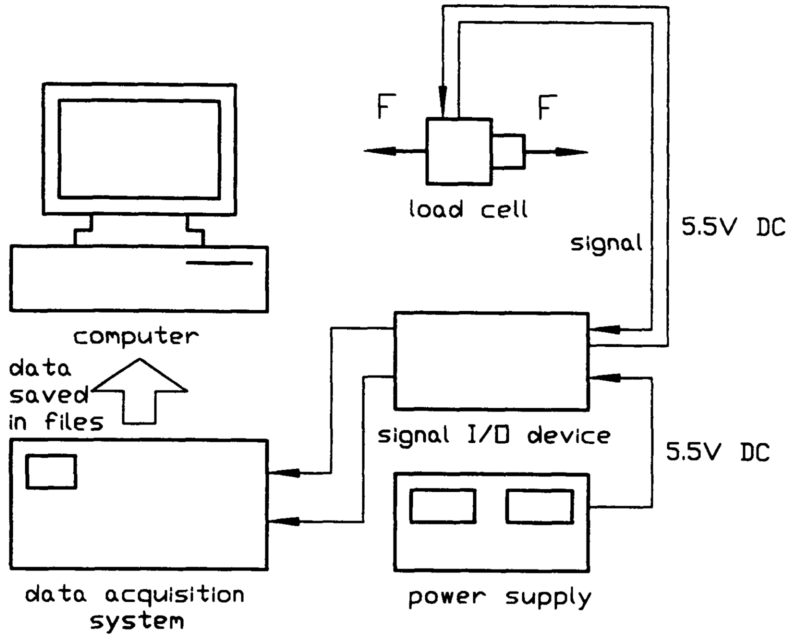


Figure 3-13: Block diagram of the data acquisition system

3.2.4 Data Acquisition System

The purpose of this testing device is to record the history of the friction force acting on the slipform from the concrete under pressure 300psi. This task of recording data is accomplished by a data acquistion system as shown in Figure 3-13. From the 0-2000lbs load cell connected to the driving system, we can read the voltage changes and translate them into the force. The load cell is calibrated to work at 5.5V DC, and it has a linear relation between the applied force on it and it's output voltage by

$$Force(lb) = 63535.511 \times \frac{V_{out}}{V_{in}}$$

where V_{in} is 5.5V DC.

From the computer software, we can read the output voltage and input voltage by any time increment, and it can save the data in files compatable with some spreadsheet software, from which we can analyze the date by looking at the history of the friction force by tables and charts. The results of the tests will be discussed in chapter 6.

Chapter 4

The Concrete Mix

4.1 Basic of Concrete

Concrete is a composite of aggregates and paste made of cement and water. The basic components of concrete are shown in Table 4.1. The functions of paste are to bind the aggregates together and to make the concrete fluid and workable before setting. The functions of aggregates are to increase the strength of concrete because of it's high strength, to decrease the volume shrinkage caused by the paste, and to decrease the cost. The typical distinction between fine and coarse aggregates are 4.75mm (or 0.187in).

Usually, concrete reaches its initial setting in 2-5 hours because of hydration, and reaches its final setting after 4-8 hours. It's strength keeps on increasing

Table 4.1: The components of concrete

component	**paste**	**mortar**	**concrete**	**special concrete**
cement	x	x	x	x
water	x	x	x	x
fine aggregate		x	x	x
coarse aggregate			x	x
admixture				x

very fast in the first 7 days, and slowly thereafter. It keeps on increasing even after years, but in a very slow speed.

Types of Cements

There are five types of Portland cement:

(a) Normal concrete: Type I Portland cement for normal use

(b) Moderate concrete: Type II Portland cement for medium hydration heat and higher resistance to Sulfate

(c) High-Early-Strength concrete: Type III Portland cement high early strength for use in cold weather or special situations like tunnel or highway maintenance

(d) Lower-Heat concrete: Type IV Portland cement for lower hydration heat but low early strength

(e) Sulfate-Resisting concrete: Type V Portland cement for high resistance to Sulfate

The type of cement suggested by Kelley's research is the Type III Portland cement with high early strength.

Types of Chemical Admixtures

From the ASTM standard, there are seven types of chemical admixtures:

(a) Type A: water reducing admixtures

(b) Type B: retarding admixtures

(c) Type C: accelerating admixtures

(d) Type D: water reducing and retarding admixtures

(e) Type E: water reducing and accelerating admixtures

(f) Type F: water reducing high range admixtures

(g) Type G: water reducing high range and retarding admixtures

The type of chemical admixture suggested by Kelley's research is the Type F water reducing and accelerating admixtures (or called superplasticizer, fluidifier) to improve the pumpability of the concrete without retarding the time of the initial set.

The principle of the water reducer is that: usually the surfaces of the cement powders are non-uniformly charged and attract each other. By adding the water reducer, the surfaces become similarly charged and the particles repel each other. The function here made the cement spread over the water without sticking together. Therefore, we can decrease the use of water and reach a higher strength, or we can achieve higher flowability of the concrete with the same amount of water.

The superplasticizer has the effect of reducing water to 15-30%, it can reduce the water/cement ratio to reach high early strength. It can be added up to 0.5-2.0% without retarding the setting of the concrete like the traditional water reducer. At the same time, it can increase the pumpability if the same amount of water is used.

Water Cement Ratio

The ratio of the mix water to cement determines the strength of the concrete. A w/c weight ratio of 0.4 is typically used as the best approximation of "complete hydration" with the understanding that there may be a small amount of unhydrated cement and some capillary porosity. A higher w/c ratio means that the concrete flows more easily, but it will not reach it's initial set as soon as the lower w/c ratio. And a lower w/c ratio means that the concrete has larger amounts of unhydrated cement inside.

There are two empirical formulas of the strength after 28 days for reference, but

Table 4.2: Reference value for the design of concrete mix

Max. size of gravel (in)	sand/gravel volume ratio (%)	water amount (kg/m^3)
3/8	61	209
1/2	53	199
3/4	45	187
1	41	178
2	33	158
6	28	125

they all depend on the different cement companies and different sources of the aggregates[1].

$$\sigma_{28} = \frac{14000}{10.4^{w/c}} psi$$

or

$$\sigma_{28} = 700 \times (1 - w/c) kg/cm^2$$

The w/c ratio suggested by Kelley's research is the lower, the better to reach a very high early strength.

Sand Cement Ratio

The size of the coarse aggregate should be less than the 1/5 the diameter of the pumping pipe. From Table 4.2, we can get the sand/gravel volume ratio and the amount of water needed.

Simply speaking, the design of the concrete mix follows the following steps:

(a) decide the needed strength

(b) decide the water/cement ratio by empirical formulas

(c) decide the maximum size of gravel

(d) find the sand/gravel volume ratio and water amount from Table 4.2

(e) calculate the cement needed, sand needed, and gravel needed from the values above

4.2 Specific Mix for CTBM

From Marsh's research, he referred to the concrete mix from a concrete liner company, which is :

cement

water 0.45 times the weight of cement

gravel 2.26 times the weight of the cement

superplasticizer 0.019 times the weight of the cement

fly ash 0.15 times the weight of the cement

citric acid 0.001 times the weight of the cement

From Darrow's research, shotcrete is suggested, which has 28 day strength $\sigma_{28} = 210 - 480 kg/cm^2$. The strength of 1-3 hours is 0 for Type I cement, 7 kg/cm^2 for shotcrete with $CaCl_2$, and 83 kg/cm^2 for Type III cement or Type I cement with accelerator [2]. And the ingredients of the shotcrete is:

cement 15-20%

water w/c=0.3-0.6

gravel max. size = 12.7mm=0.5in, 30-40%

sand 40-50%

accelerator necessary when used with type I cement

From Kelley's research, the mix should be:

- Type III Portland Cement
- low w/c ratio

- superplasticizer added

In our experiments, the mix of concrete is chosen to meet the necessary features of the real CTBM liner. However, it is constrained by the size of the testing device. The coarse aggregates are not used, only sand is used to make a mortar instead of concrete. The mix of concrete is as follows:

cement Type III Portland Cement (High Early Strength)

water/cement 0.40

sand/cement 1.30

superplasticizer/cement 0.02

Furthermore, other mixes of concrete are made to do the tests to see the performance. Actually, this mix performed the best in the testing device since it was pumpable but not too fluid, and it reached its initial set in 1 hour.

The cement and mortar sand were bought from Waldo Bros. Company (202 Southampton St., Boston, MA 02118-2789, Tel (617)445-3000), and the superplasticizer were samples made by W.R. Grace & Co.

Chapter 5

Experimental Procedure

5.1 Preparation of the Experiment

5.1.1 Safety Test of the Air Pressure System

The most dangerous part in this testing apparatus is the air pressure container for 100 psi, instead of the hydraulic system for the high pressure up to 5,000psi. This is because of the compressibility of the air, the 100 psi compressed air stores a lot of energy. It can hurt people if the container breaks and explodes. On the other hand, the hydraulic system with high pressure fluid does not store so much energy inside. Once there is a leak or break, the pressure goes down immediately. However, people should be still careful while operating the hydraulic system at high pressure. The danger can be avoided by careful operations.

The pressure container for concrete was tested for safety. The testing device is shown in Figure 5-1. The principle is that the water is not compressible, so it will not store too much energy. If the container breaks at 100 psi water pressure, it will not explode and cause any tragedy. Therefore, before the real test using compressed air in the container, we use pumped water to simulate

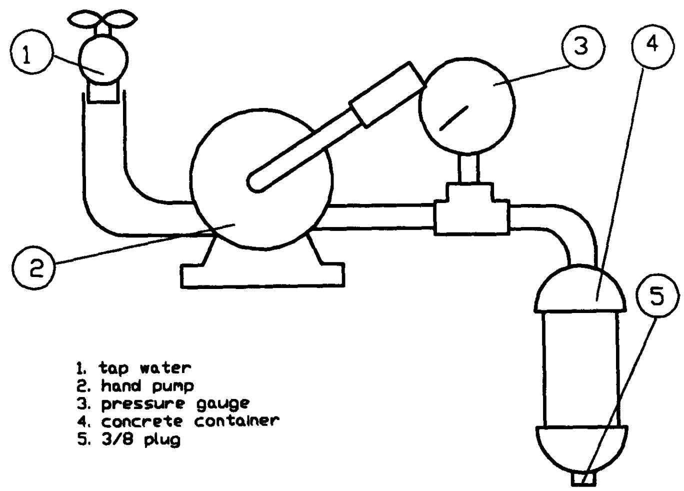


Figure 5-1: Safety test of the air pressure system

the pressure and see if the container breaks to ensure the life of the operator to do the experiment [9].

The device is simple, it includes a hand pump, a pressure gauge up to 300 psi, and pipes and fittings. It pumps the tap water into high pressure water to fill the concrete container. In the safety test, we went up to 200 psi and assured the container is at least 2 times stronger than the need 100psi in the real experiment.

5.1.2 Safety Instructions on Operating Hydraulic System

Hydraulic power is one of the safest methods for applying force to the work when used correctly since it does not store as much energy as the compressed air. However, if there is a leak and operators are very close to the leak, the high pressure fluid can cut people's skin. Therefore, operators should follow the safety instructions:

- Choose the parts all rated up to 10,000psi. (ex.3/8" schedule 80 seamless pipe)
- Tighten connections properly with Teflon tape for seal.
- Do not over-tighten the connections. It will cause strain on the threads and cause fitting failure at pressures below rated capacity.
- Remove air trapped in the hydraulic system. Air trapped inside will increase the danger when there is a break. Follow the instructions from the manufacturer's catalog in Appendix D to remove the air.
- Do not touch the hoses or fittings with pressure in the system.
- Avoid sharp bends in hoses.
- Read the safety instructions from the manufacturer's catalog.

5.2 Designed Method to do the Experiments

The design of the testing apparatus is constrained by many limits. At first, the concrete had a big shear resistance when we pump it through pipes. From Section 3.2.2, we obtained the value of pressure drop 27psi when we pump concrete into a 3/8" pipe for 25 inches. The resistance of fresh concrete constrains the length of the pipes, and the size of the space to pump concrete constrains the diameter of the pipes. Therefore, we cannot design a machine which runs continuously with a 20 ft long screw rod to pull the 20 ft long slipform with 20 ft long concrete pipe goes under the pressure presses as well as other structures which are already set up. Instead, we have to separate the 20 ft long testing spaces into small sections of 16 in long, and to run the testing device periodically. After finishing the test on one section, we have to stop the machine, set up the next section, and start it again.

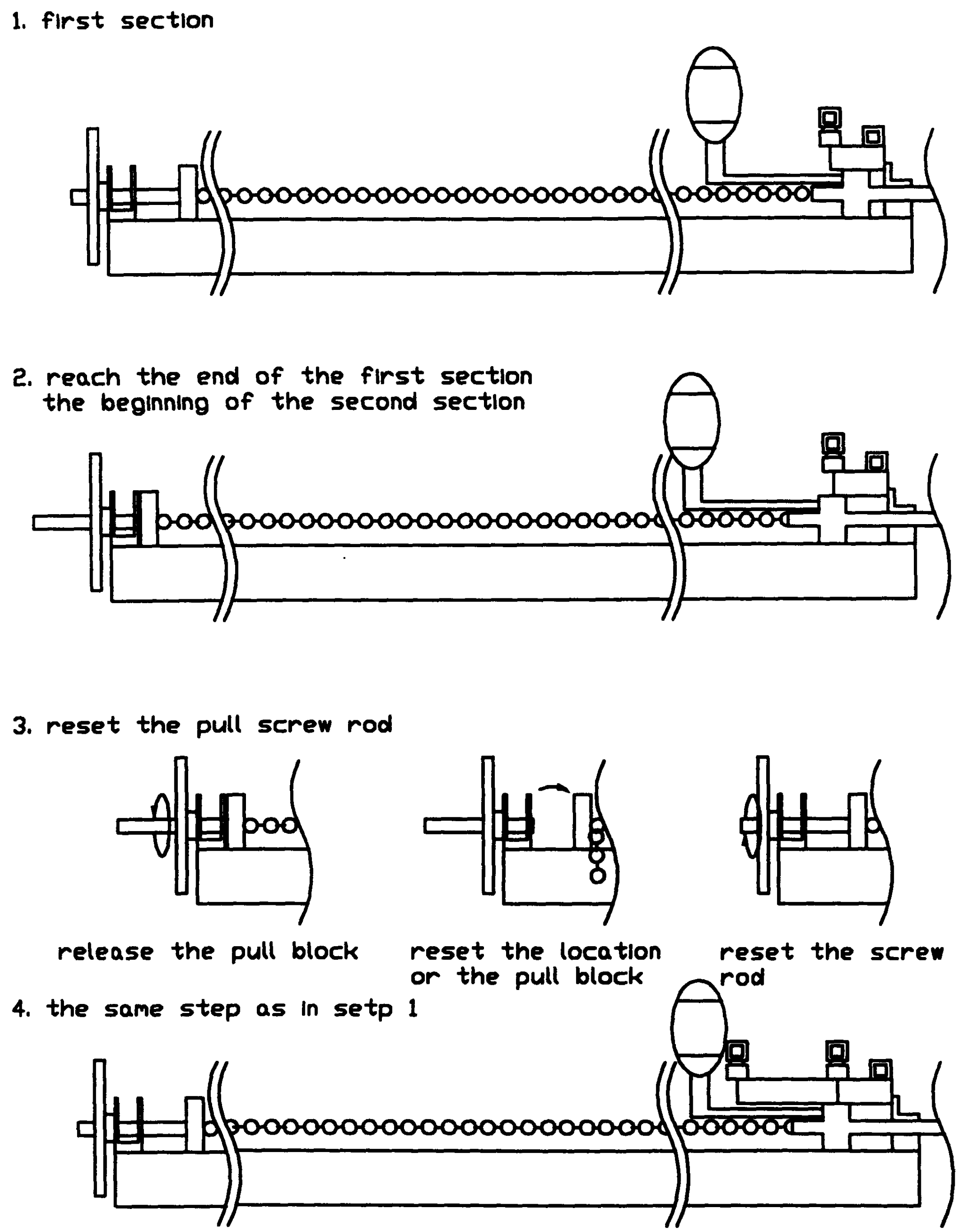


Figure 5-2: Operation of the experiments

From Figure 5-2, we can obtain a standard process to do the test:

Step 1 As in the first drawing

(a) Clean the machine if there is any concrete left in the machine from the last test.

(b) Assemble the machine (driving system, concrete pumping system, hydraulic system)

(c) Prepare mixes of cement and sand for the use in the test.

(d) Set up the data acquisition system by adjusting a 5.5V DC power supply, connecting the load cell cable to the system, adding a task name, choosing the channels, setting time increment, and start it.

(e) Set up the structure of the first section.

(f) Pump the fluid to the desired pressure, hydraulic cylinders will extend out to full stroke.

(g) Pour in the mixed fresh concrete in the container, close the container, and start the air pressure.

(h) Start the motor.

Step 2 As in the second drawing

(a) Check if concrete flows into the channel from the clearance between the pressure press and the steel angles.

(b) If no concrete flows into the channel, try to increase the air pressure or apply some vibration on the concrete container.

(c) If still no concrete flows out, it means this mix of concrete is not pumpable in this device, stop here.

(d) If concrete flows out, periodically stop the air pressure, open the concrete container to check if it is short of concrete, refill it if necessary, close it and apply air pressure again.

(e) Wait till the head appears from the end of the pressure presses.

Step 3 As in the third drawing

(a) Stop the motor, reset the driving screw rod by 1)releasing the pull block, 2)removing the pull block back to the start position (at least 16 inches from the end position), reconnecting the chain, 3)and turning the screw rod forward to meet the pull block and screw into it. During the setup, the sprocket is constrained by motor and won't rotate.

(b) Check the set screw on the motor shaft, tighten it if it is loose.

(c) Release the hydraulic pressure, set up the structure of the next section, put a hydraulic cylinder on top of the pressure press, and pump the fluid again to the desired pressure.

Step 4 As in the fourth drawing

(a) Start motor, periodically stop the air pressure, open the concrete container to check if it is short of concrete, refill it if necessary, close it and apply air pressure again.

(b) Wait till the head appears at the end of the pressure press.

(c) Repeat the process Step 3 until setting up the third section (the fourth hydraulic cylinder).

These standard processes continue until we want to apply pressure on the curing concrete. Up to now, a 1/4" space is provided for the hydraulic cylinders to extend out without external load, thus the hydraulic cylinders are only there to keep the pressure presses in position as shown in Figure 5-3, without applying pressure on the concrete. If we want to apply pressure, we put spacer pads on the hydraulic cylinders. The procedure designed for this experiment is to start to apply pressure on the concrete after 3 sections (48 inches) have been

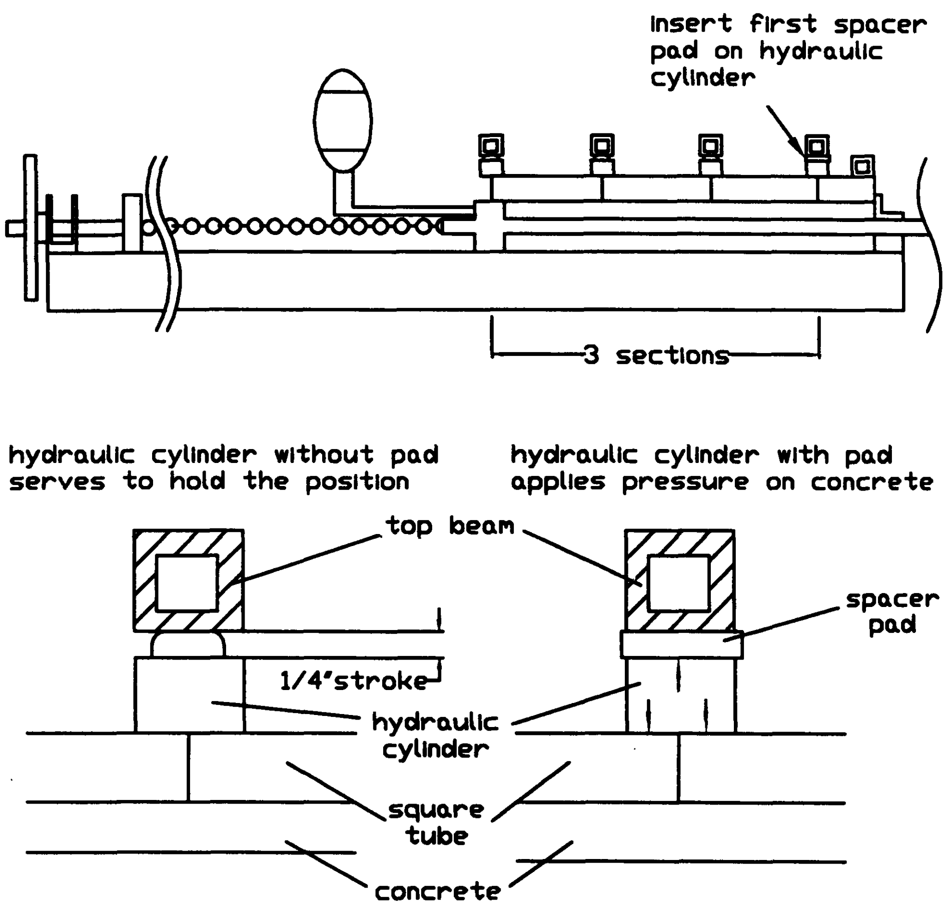


Figure 5-3: Adding spacer pads on the hydraulic cylinders

traversed since the fresh concrete is not able to take the pressure without being squeezed out of the test channel.

Step 5

(a) From the setup of the fourth hydraulic cylinder, start to put a spacer pad on the first hydraulic cylinder. That means, when setting up the (n)th hydraulic cylinder, put a pad on the (n-3)th hydraulic cylinder to start applying pressure on the (n-3)th section of curing concrete.

(b) Repeat the process Step 3 remembering to place the pad for the (n-3)th hydraulic cylinder.

5.3 Data Analysis

The purpose of the tests is to measure the friction acting on the slipform form concrete at different curing conditions along the length of the channel. The data of the load cell is collected and stored in files compatible with spreadsheet software. The data will be processed by computer and printed out in charts.

Chapter 6

Results and Discussion

6.1 Pumpability of Concrete

Because of the limit of the size of the testing apparatus, the pipes and inlets for the concrete are constrained to a small dimension. The pumpability is strongly influenced by the size of aggregate. In chapter four, we have calculated the pressure drop of concrete after the 25" long, 3/8" pipes is 27psi. However, this typical value varies when the mix of concrete changes. For example, if a mix of concrete of w/c=0.4, sand/cement=1.5, and superplasticizer/cement=0.02 is used, the concrete is not pumpable at all in this machine when the air pumping pressure goes up to 100 psi. On the other hand, if a mix of concrete of w/c=0.45, sand/cement=1.0, and superplasticizer/cement=0.02 is used, the concrete flows out without any applied air pressure. The pumpability of the concrete is strongly influenced by:

- water/cement ratio
- sand/cement ratio
- maximum sand dimension
- diameter and length of the pipe

- bends of the pipe
- sudden cross section area reduction in the pipe
- with or without superplasticizer

To increase the pumpability, we could increase w/c ratio, decrease sand/cement ratio, or increase superplasticizer into the mix. However, increasing w/c ratio decreases the early strength of the concrete, and decreasing sand/cement ratio decreases the strength of the concrete and causes more shrinkage when concrete is curing. Thus we keep the w/c ratio as low as possible, sand/cement ratio as high as possible, and add superplasticizer up to 2% the weight of cement.

From our tests, we found that when w/c ratio is around 0.40, the property of concrete is very sensitive to the variances of w/c ratio [4]. When w/c=0.42, the concrete is very liquid and reaches its initial setting after more than four hours. When w/c=0.38, the concrete is not pumpable in this device at a pumping pressure of 100 psi. Thus the range of the w/c ratios in the following experiments are chosen to be 0.40, 0.41, and 0.42. The w/c ratio of 0.40 is the typical value in the following tests, the ratios of 0.41 and 0.42 are chosen to be references for comparison.

Because of the dimension limit in the testing device, coarse aggregates are not used in the concrete mix. Only mortar will be used to accomplish the tests. The mortar sand was filtered by ASTM No.30 sieve (590 microns, or 0.0232 in) to filter out the large size sand to prevent concrete clogging in the pipe. This value was calculated by the consideration that the size of sand cannot be bigger than 1/5 the diameter of the pumping pipes. The diameter of the pumping pipe is 3/8", therefore the biggest size of sand should be 0.075 inches. This size of sand can be sieved by ASTM No.16 sieve (0.0469 in) or ASTM No.30 sieve. Considering the bends and cross section area changes in the inlet of the pumping head, we decided to apply the more conservative sieve to filter the sand.

The sand/cement ratio influences the strength of the concrete. The s/c ratio should be kept as large as possible. In our tests, it shows that when s/c ratio is higher than 1.50, the concrete is not pumpable in this device at a pumping pressure of 100 psi. When the s/c ratio is smaller than 1.20, the concrete is very liquid and very close to paste which flows through the device without the requirement of pumping pressure, and it reaches it's initial set at about four hours. Thus the range of the s/c ratio in the following tests are chosen to be 1.20, 1.25, and 1.30. The typical value used in these tests is 1.30, the ratios of 1.20 and 1.25 are used to be references for comparison.

However, regardless of the consideration of the limit of our testing device, some mixes of concrete were tried to see if they meet the requirements of CTBM, and we found that a mix of mortar is appropriate for CTBM. The specification of the mix is w/c=0.35, s/c=2.00, and superplasticizer/c=0.01. It reaches its initial set in less than one hour, and reaches its final set in 3 hours.

6.2 History of Friction Forces

Figure 6-1 to Figure 6-4 are the results of tests of the same material: w/c=0.40, s/c=1.30, and supreplasticizer/c=0.02 at different speeds and overburden pressures. The charts show the history of the friction forces acting on the slipform.

From Figure 6-1, we can understand the meaning of the charts. X axis presents the time by second, and Y axis presents the force measured from the load cell connected to the pulling chain. Each gap of 300 seconds (5 minutes) means the stop of the machine and the setup of the next 16 inch section. In Figure 6-1, we have run the machine for 8000 seconds from x=700 to x=8700, that means the oldest concrete pumped into the first section of the testing device is 8000 seconds (2 hr. and 13 min.) old.

The values of pressures shown in the charts are the hydraulic pressures applied in the hydraulic cylinders. The ratio between the hydraulic pressure and the

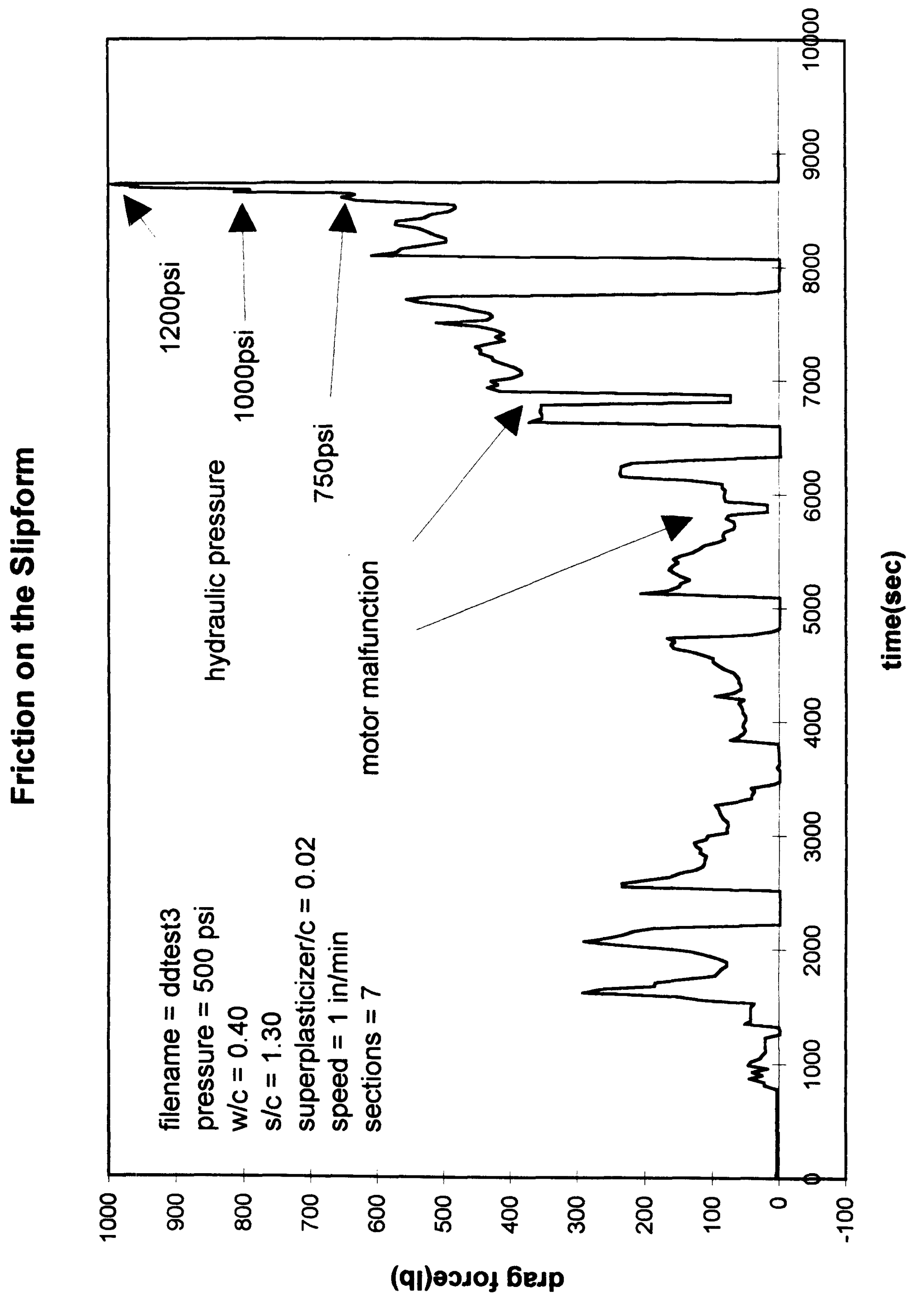


Figure 6-1: Test result 1

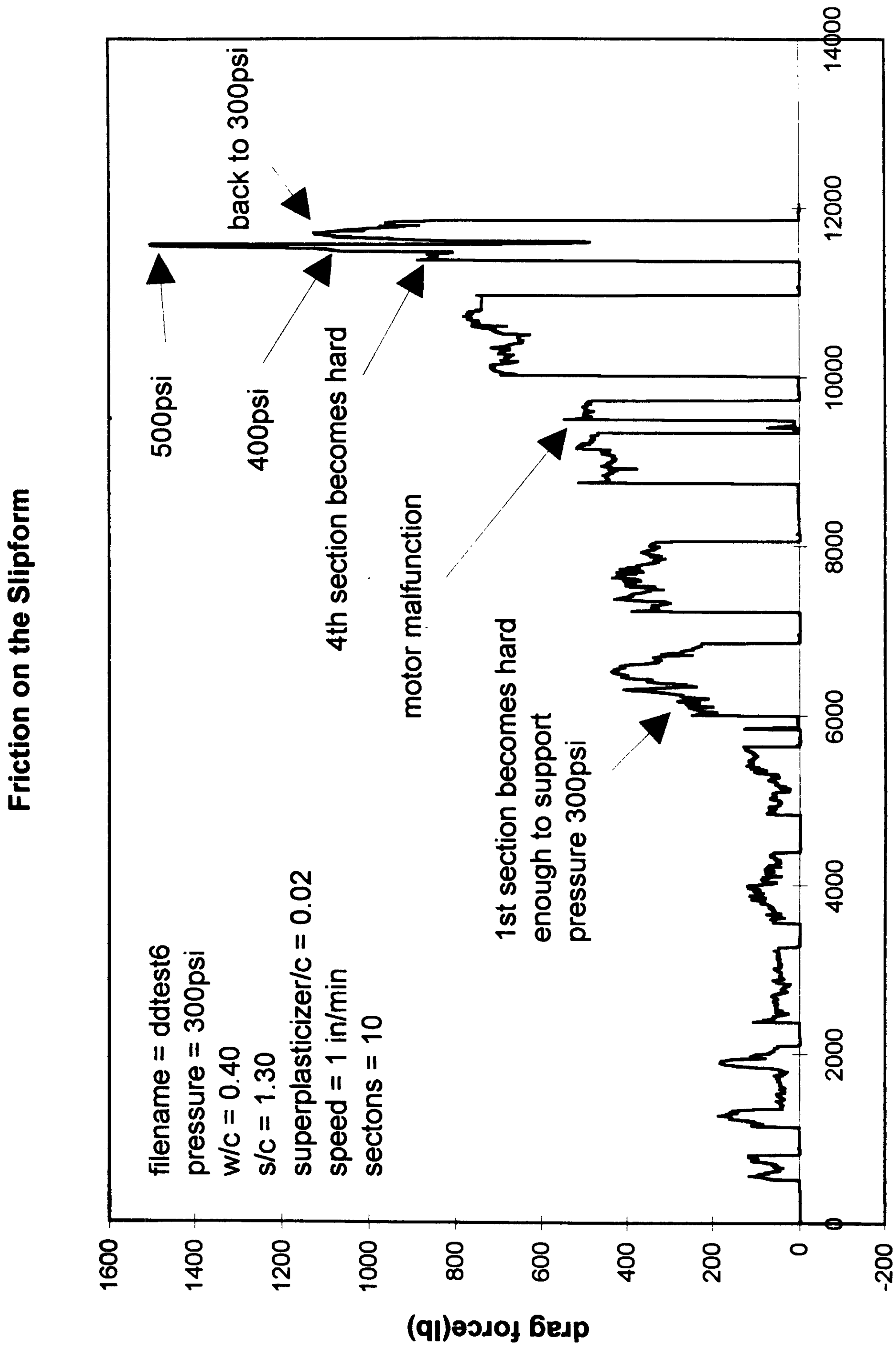


Figure 6-2: Test result 2

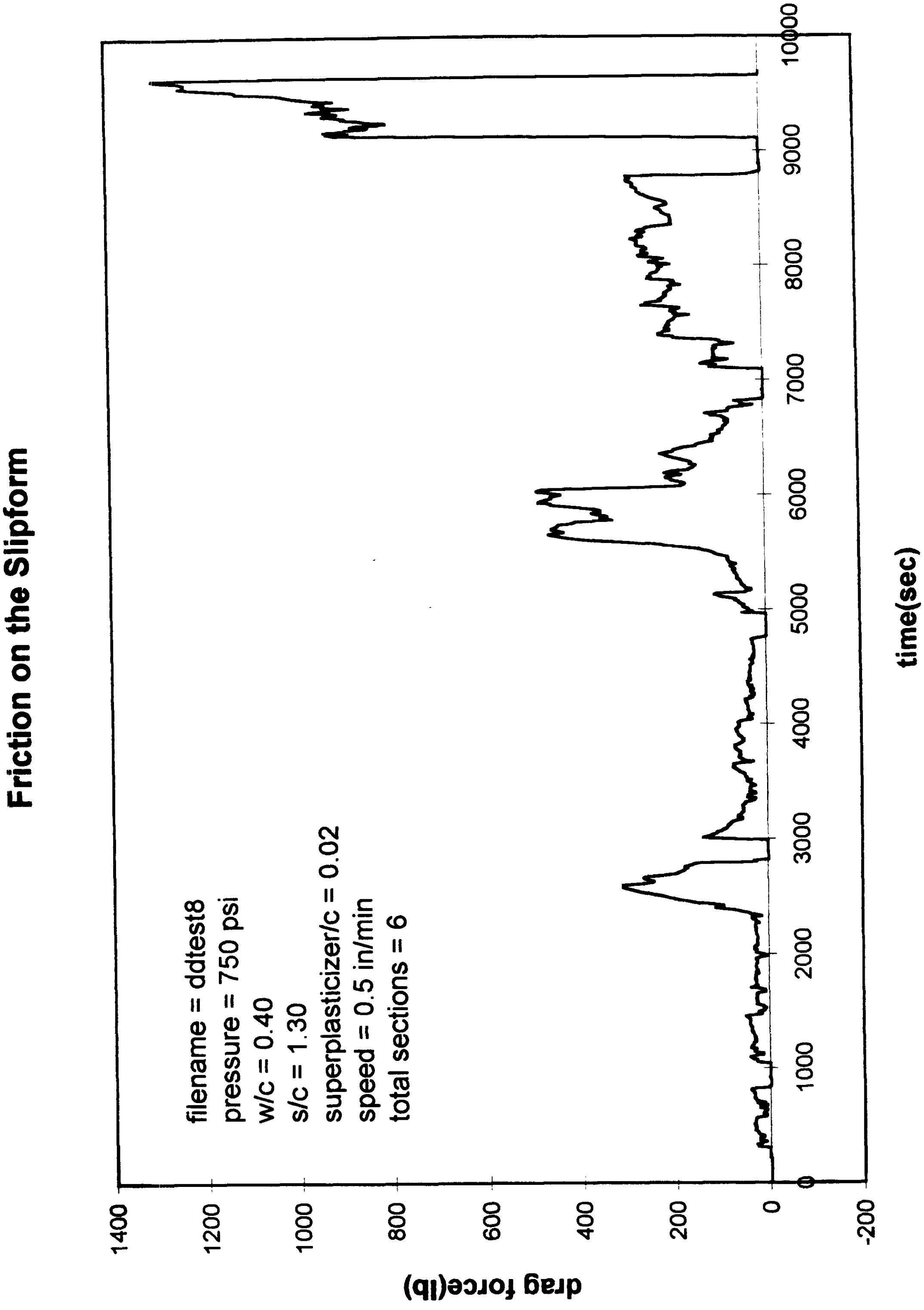


Figure 6-3: Test result 3

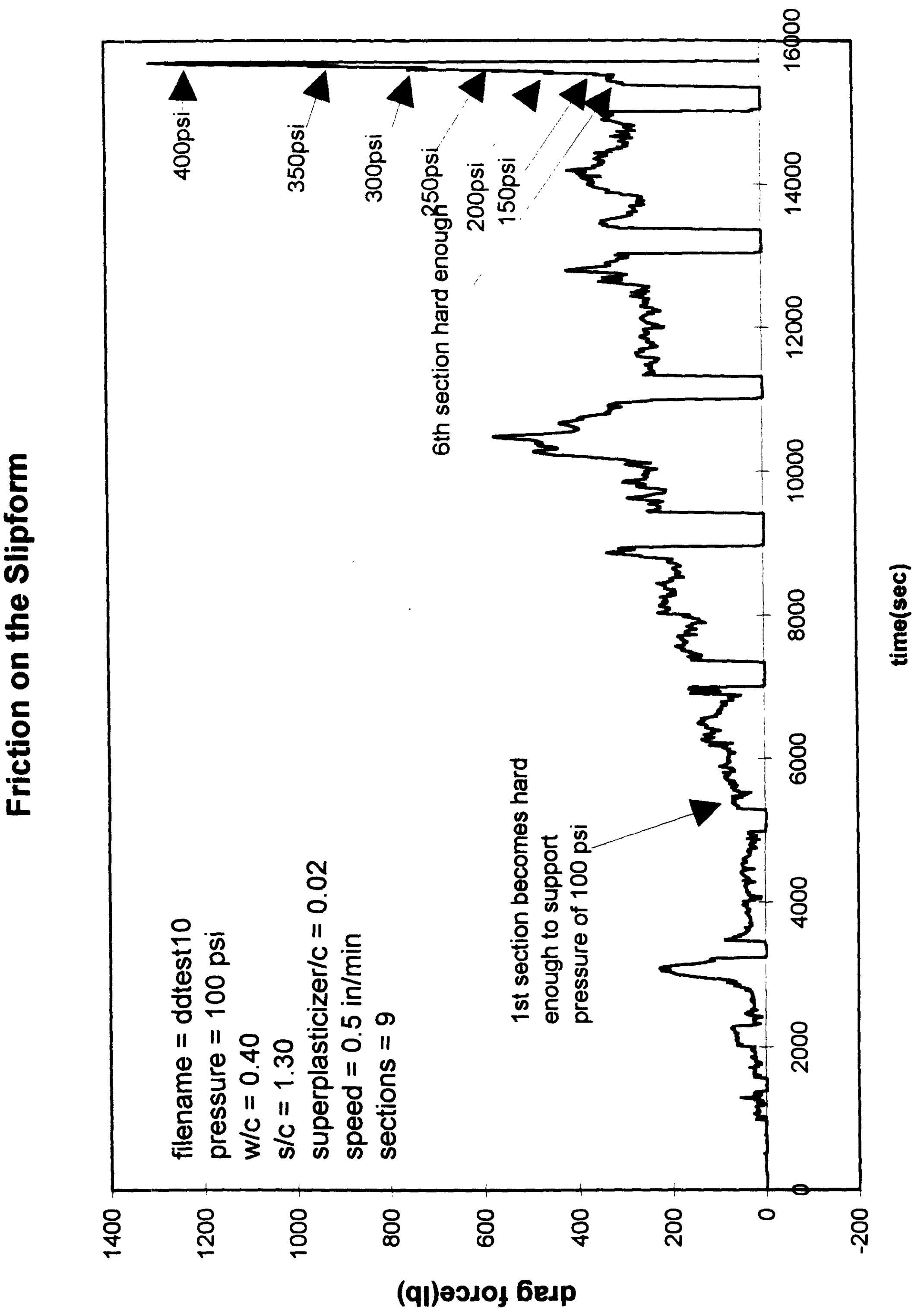


Figure 6-4: Test result 4

pressure applied on the concrete is

$$\frac{P_{concrete}}{P_{hydraulic}} = \frac{\frac{F_{hydraulic}}{Area}}{P_{hydraulic}} = \frac{\frac{10,000lbs}{16in^2}}{10,000psi} = \frac{625psi}{10,000psi} = 0.0625$$

The unusual curves in Figure 6-1 include the gaps caused by motor malfunction and the peaks caused by the friction from the machine itself. The motor failed when the set screw on the motor shaft loosened. The motor cannot transmit power to the driving system and we had to stop the motor and tighten the set screw. The peaks caused by the friction from the machine itself will be discussed in the next section. Another unusual feature in these charts is that no forces go higher than 1,600 lbs because the controller cut off the power when the force goes up to more than 1,600 lbs.

At the end of the tests of Figure 6-1, Figure 6-2, and Figure 6-4, we applied different pressure on the hydraulic cylinders to see the relationship between the pressure and the friction.

From Figure 6-5 to Figure 6-8, these are the results of the tests done to measure the relationship between the pressure and the friction at different times. Results 6,7,8 have the same material in test result 4. After we have done test 4 of the history of friction force, we simply waited for 0.4,0.8, and 1.0 hour and started the machine again to measure the friction at different hydraulic pressures. Result 5 has the same material in test result 3.

From Figure 6-5, we find a static friction when we start the machine, which is a little bigger than the dynamic friction. The unusual curve in the figure happens when it reaches high pressure and force oscillates. That is because the motor starts to struggle and tilts, the ladder chain connecting the two sprockets becomes misaligned, and the sprockets start to run noisily.

Tests of Figure 6-9 and Figure 6-10 are the references which have different mixes of concrete. Test 9 is not very successful. The two peaks in the charts are made by mechanical malfunction of the testing device because the head of concrete

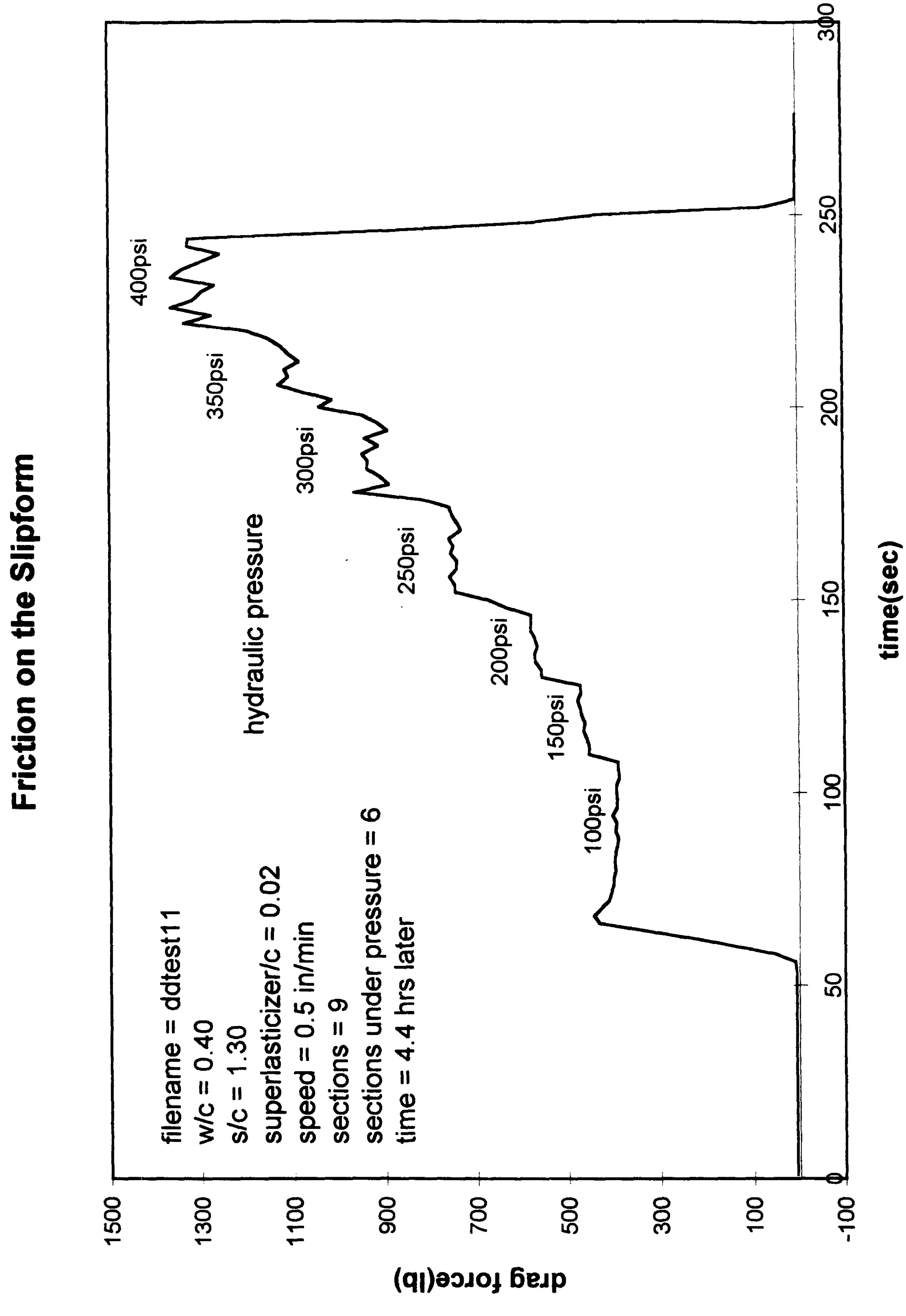


Figure 6-5: Test result 5

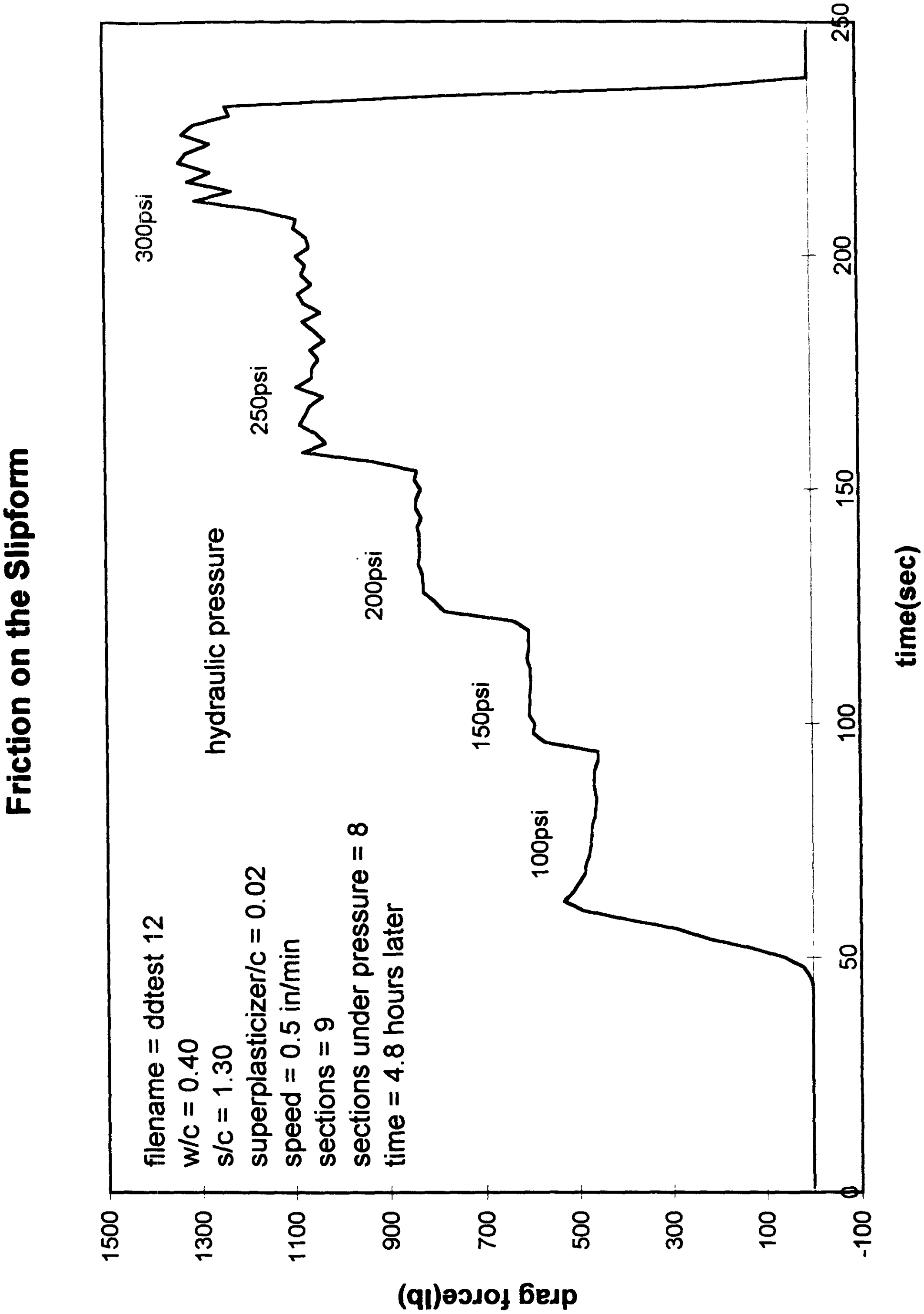


Figure 6-6: Test result 6

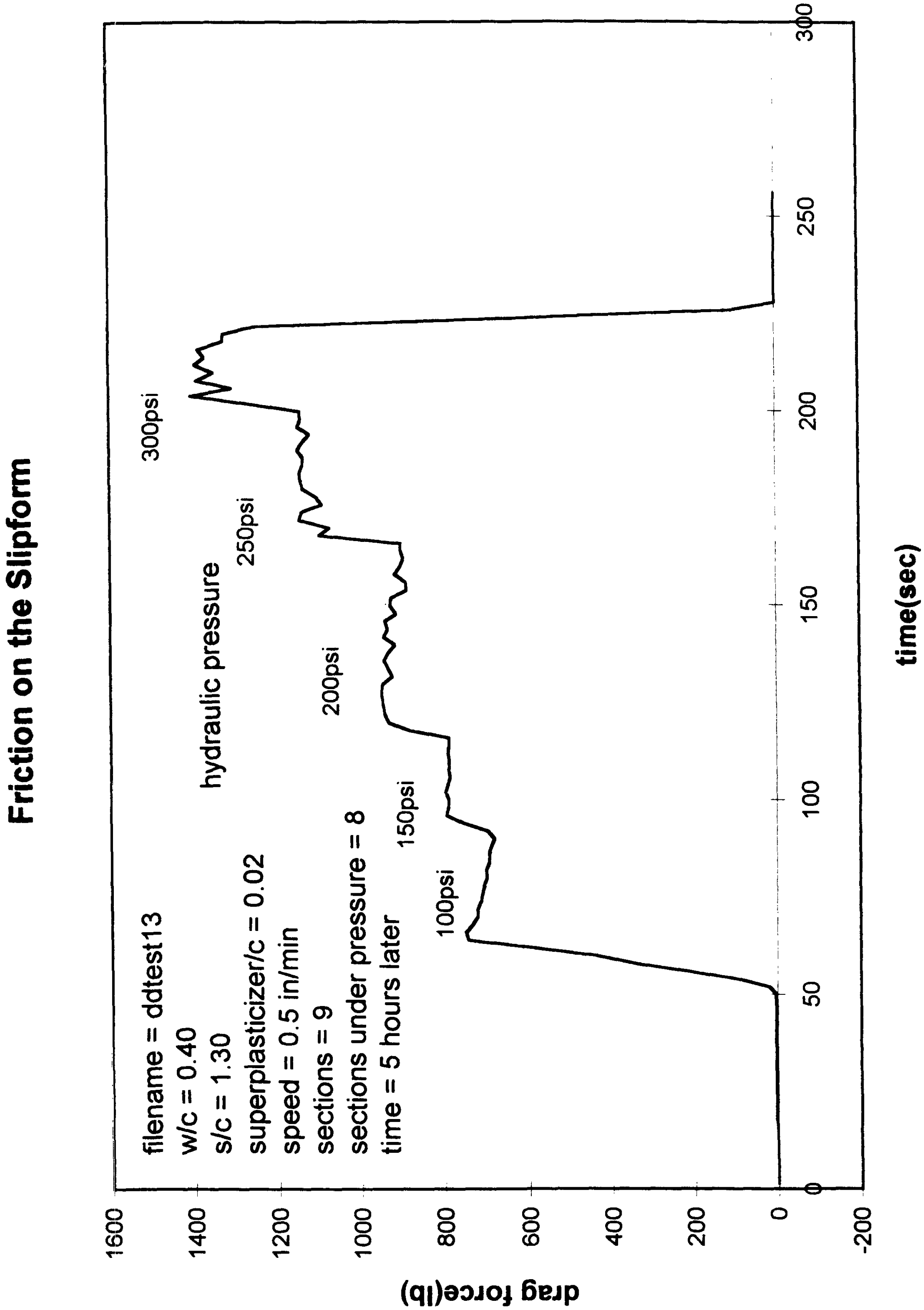


Figure 6-7: Test result 7

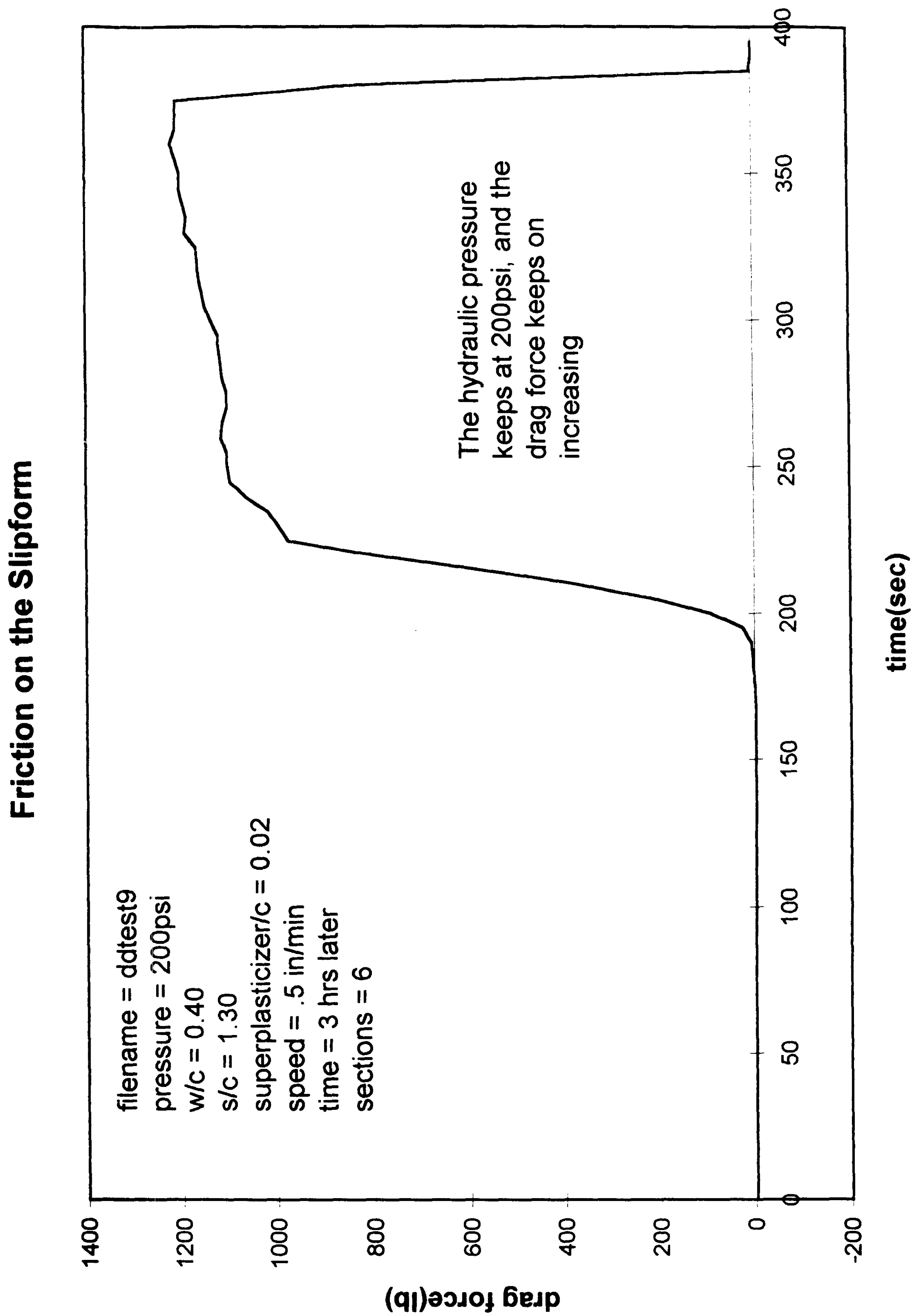


Figure 6-8: Test result 8

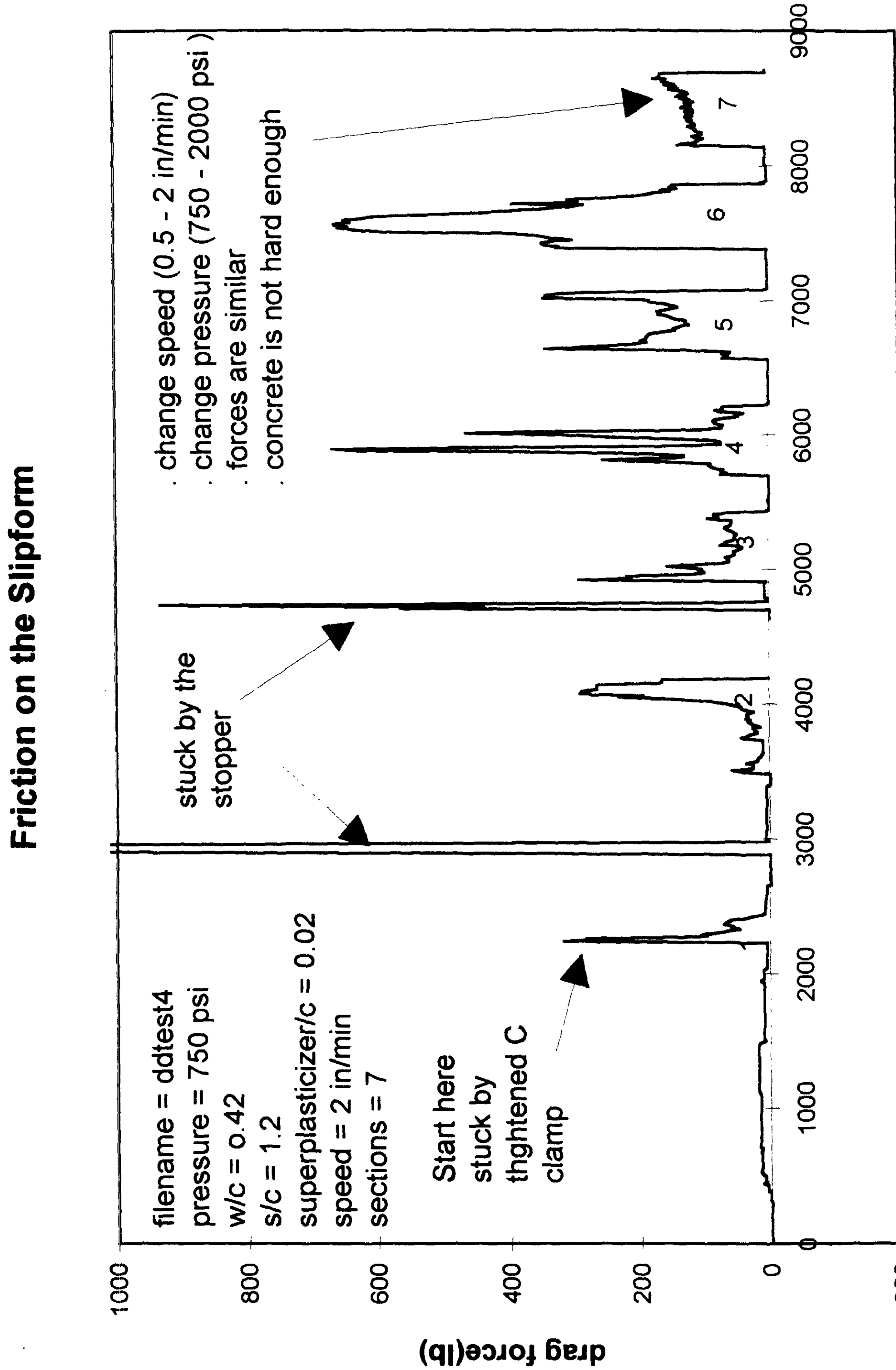


Figure 6-9: Test result 9

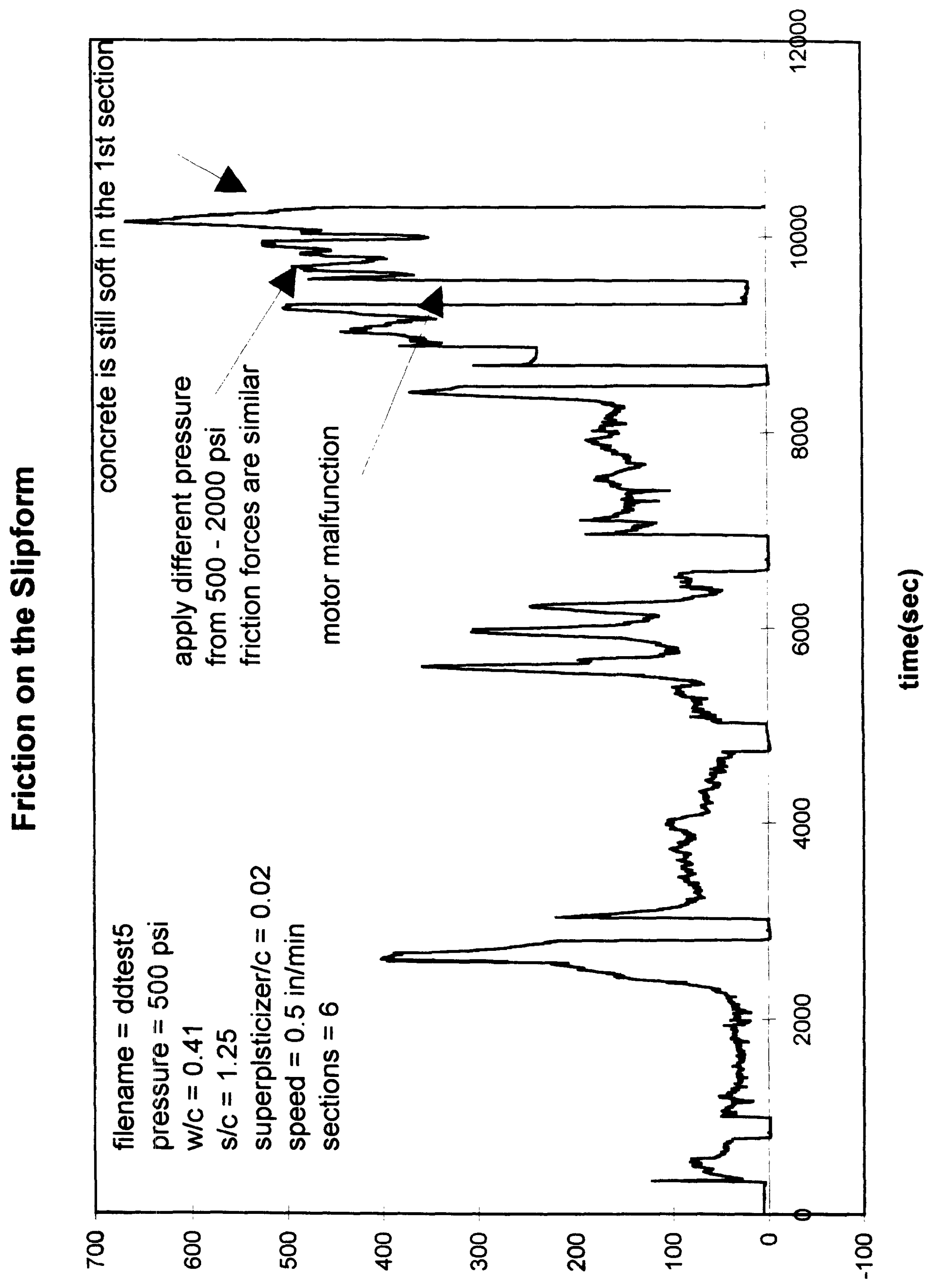


Figure 6-10: Test result 10

inlet was stuck by a stopper which has been replaced by wire in the final design. Regardless of the strange peaks shown in the figure, we can tell from the data after section 7 that concrete still has not reached its initial set and the friction is still very low after 2 hours. The w/c ratio is 0.42 and s/c ratio is 1.20 in Test 9. Concrete used in Test 10 is a mix of w/c ratio = 0.41 and s/c ratio = 1.25, it reaches its initial set at about 2 hours later.

6.3 Error in the Tests

There are many possible sources of error in these tests. First, the friction caused from the machine itself is the major error in these test. A so called empty test is done to measure the friction of the machine itself without pumping in any concrete. The result is shown in Figure 6-11. We found that the typical friction along the machine is about 25-50lbs, however there is a peak at the end of section 2 that goes up to 230lbs. This peak is because of the tightness at the end of section 2, and it causes some difficulties for the head to go through. This peak can be seen in every test result clearly. The other friction of 25-50lbs is acceptable.

Another error can happen is the linearity of the load cell. It was assumed that the load cell has a linear relation between the load and the output voltage. However, it is not true when the force is small. The load cell has a region of accuracy. Even it is rated from 0 - 2000lbs, it doesn't read correct load when the force is too small or too big.

Another error can happen when air pressure is applied to the concrete, it causes propulsive force on the head of concrete inlet. The maximum propulsive force is presented as

$$F = (p - \Delta p) \times Area = (100 - 27) \times 1 = 73lbs$$

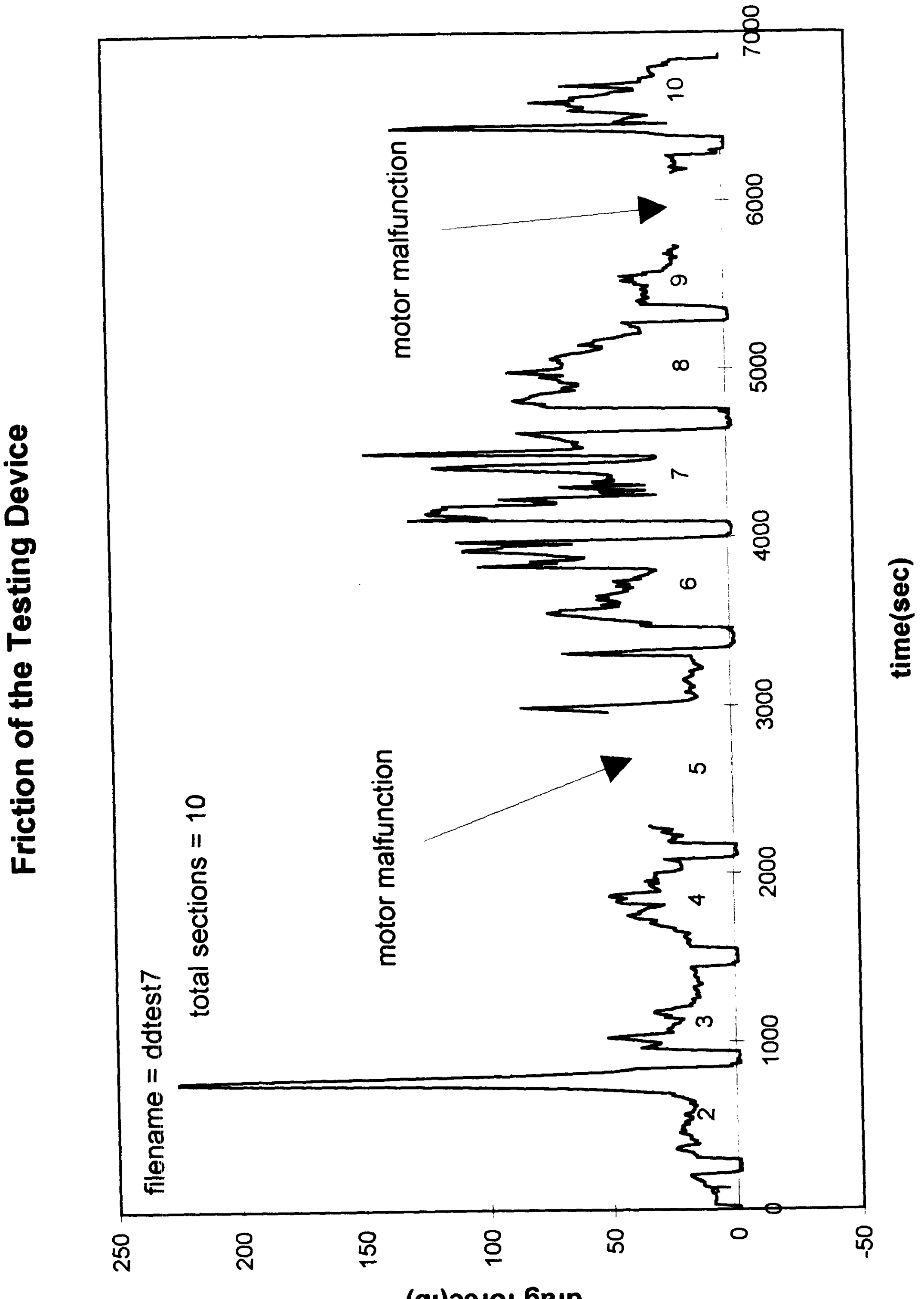


Figure 6-11: Friction caused by the machine itself

	0.5	1	1.5	2	2.5	3	3.5	4	Average Velocity	pressure	f after set	u
test1	120	120	200	500					0.012	31.2	6.94	0.22
test2	80	80	250	410	550	800			0.013	18.8	4.17	0.22
test3	50	80	100	300	800				0.0077	46.9	12.6	0.27
test4	80	80	150	220	250	280	300	350	0.0082	6.25	1.2	0.2

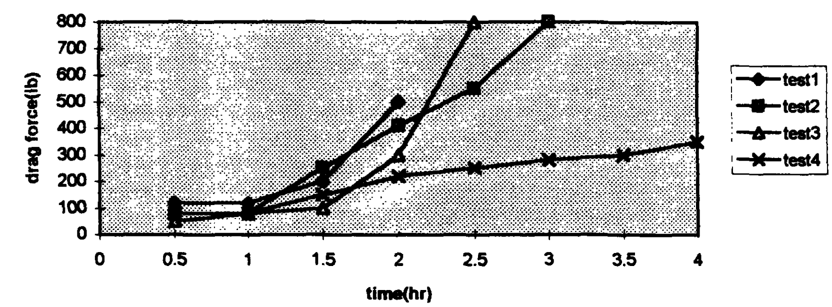


Figure 6-12: Simplified test results 1-4

However, we did not apply such a big pressure on concrete. We always adjust the air pressure regulating system to make the pressure equal to zero after the pressure drop during the pipe. Still, it will cause some fluctuations of force read from the load cell.

Another error can happen when reading the hydraulic pressure gauge. The pressure gauge is rated up to 10,000 psi, the reading of pressure of 100psi is very rough. The accuracy of the gauge is also suspicious when the pressure is as low as 100psi.

6.4 Discussion of the Results

6.4.1 Friction Coefficient of the Set Concrete

Test 1-4 The results of tests 1-4 are taken to predict the friction coefficient of the curing concrete. Those four figures can be simplified and modified to Figure 6-12. In Figure 6-12, the average speed is derived by (total length)/(total time), the pressure shown in the table has been transfered to the pressure on the concrete.

The friction per surface area τ (shear resistance) at a certain time t is obtained by assuming that the drag force is continuous as shown in Figure 6-12. This assumption is acceptable because the time of the gap for setting up the machine is relatively small compared to the time of the test of each section (about 1/6). Therefore

$$dF = \tau(t)wdx = \tau(t)wVdt$$

$$\tau(t) = \frac{dF/dt}{wV}$$

$$f = \frac{(y_2 - y_1)(lbs)}{V_{average}(in/sec) \times (x_2 - x_1)(sec) \times 2(in)}(lbs/in^2)$$

where w is the circumference and V, as noted, is the average velocity.

The coefficient of friction μ is obtained similarly by

$$dF = \mu(t)pwdx = \mu(t)pwVdt$$

$$\mu = \frac{dF/dt}{pwV} = \frac{f}{Pressure}$$

In the tests, we found that when the concrete is solid, the friction coefficient μ is independent of pressure. In contrast, when the concrete is liquid, the friction per surface area τ is independent of pressure. Therefore, from the equations, we can determine the type of friction, and calculate the amount of the coefficient of friction μ or the shear resistance τ.

From Figure 6-12, we found the initial setting of the concrete of the specific mix (w/c=0.40, s/c=1.30, superplasticizer/c=0.02) is at 1 to 1.5 hours. The slope of the curve starts to increase rapidly when the concrete reaches its initial

	0.5	1	1.5	2	2.5	3	3.5	4	Average Velocity
test1(31.2psi)	10000	10000	16667	41667					0.012
test2(18.8psi)	6153.8	6153.85	19231	31538	42308	61538			0.013
test3(46.9psi)	6493.5	10389.6	12987	38961	103896				0.0077
test4(6.25psi)	9756.1	9756.1	18293	26829	30488	34146	36585	42683	0.0082

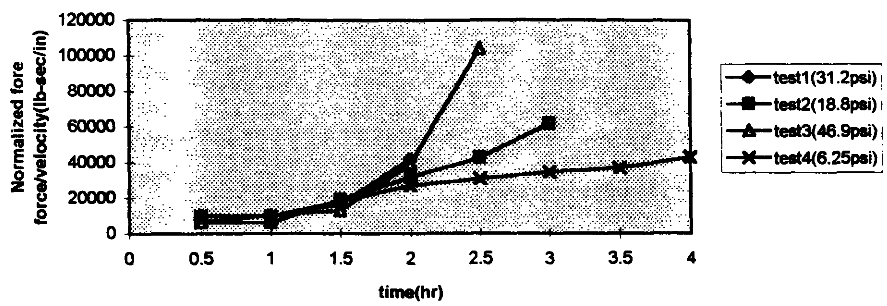


Figure 6-13: Normalized test results 1-4

set. From the experimental results, the friction from the liquid concrete is very low and is independent of the pressure, which means that the liquid concrete has a low shear resistance. After the initial set, the curve of the force has a linear tendency, which means the coefficient of friction becomes steady when the concrete reaches the initial set. The coefficient does not change slowly, it changes suddenly when the concrete reaches the initial set, presumably when the shear strength of the concrete itself exceeds the applied stress. And the results show that the value in the region of set concrete is about 0.20 to 0.27.

Since the speeds of test 1 - 4 are different, the length of the concrete is different. Thus the force shown in Figure 6-12 should be normalized by dividing it by either the length or the velocity. In Figure 6-13, we normalize it by the velocity, and we obtain four curves of the performance of concrete in the situation under different pressure only. And our new model of concrete liner will based on the normalized data.

	time(hr)\pressure(psi)	6.25	9.375	12.5	15.63	18.75	21.875
test4	4	350	400	500	600	750	950
test5	4.4	400	450	550	740	920	1100
test6	4.8	450	600	820	1050		
test7	5	680	800	930	1130		

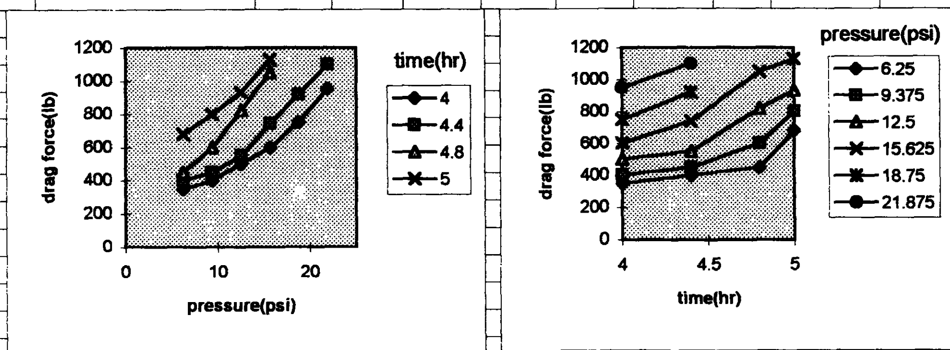


Figure 6-14: Simplified test results 4-7

6.4.2 The Relation Between Pressure and Friction Coefficient

Test 4-7 From test 4-7, we have a continuous relation of pressure-force relation relative to time of the set concrete. We can simplify and modify them and put these results in Figure 6-14. From Figure 6-14, we can see the relation between the pressure and friction from the left chart. The relation is close to linear and for design purposes, we can use the linear relation to estimate that the friction coefficient is still the same at a higher pressure. From the right chart in Figure 6-14, we see how the friction force increases when the 0-4 hour old concrete liner solidifies to 1-5 hour old concrete. The sudden increase of friction from 4.4 hr sample to 4.8 hr sample is because that 2 more hydraulic cylinders are applied to press the concrete at test 6 and test 7.

The drag forces shown in test5, 6, and 7 show that the static friction after half hour stop does not cause much trouble. This implies that in the real CTBM, the machine can be turned off for a period of time without causing much trouble with the static friction when restarting.

6.4.3 Friction Behavior of the Curing Concrete Before Set

Test 9-10 In these two tests, different mixes of concrete were used. They both solidify slowly so they can show the transition from liquid concrete to solid concrete clearly. The results show that in the transition region, the friction force is independent of the overburden pressure.

Figure 6-9 (test 9) shows the history of friction force of a specific mix of concrete, which is still soft after 2 hours. The result in this experiments shows a lot of unpredictable peaks. However, the last section can show us the shear resistance of the liquid concrete because of its clear performance, and the friction does not change because of the change of pressures and speeds. From the equation shown in the last section, τ=1.5psi before the initial set of the concrete. (Marsh's research:0.1psi, Darrow's research:0.4psi) It is bigger than the values in the previous research, it is so because the concrete is already 2 hours old, and the shear resistance is increasing when it is becoming older.

Figure 6-10 (test10) shows the history of friction force of another mix of concrete, the performance of this concrete is similar to that in test 9. The concrete is soft, and the friction doesn't change when a different hydraulic pressure is applied. From the curve, we can calculate the shear resistance τ of this concrete at 2.7 hours old is about 5psi, the relative coefficient of friction is 0.16. This implies that when the concrete keeps on hardening and the shear resistance keeps on

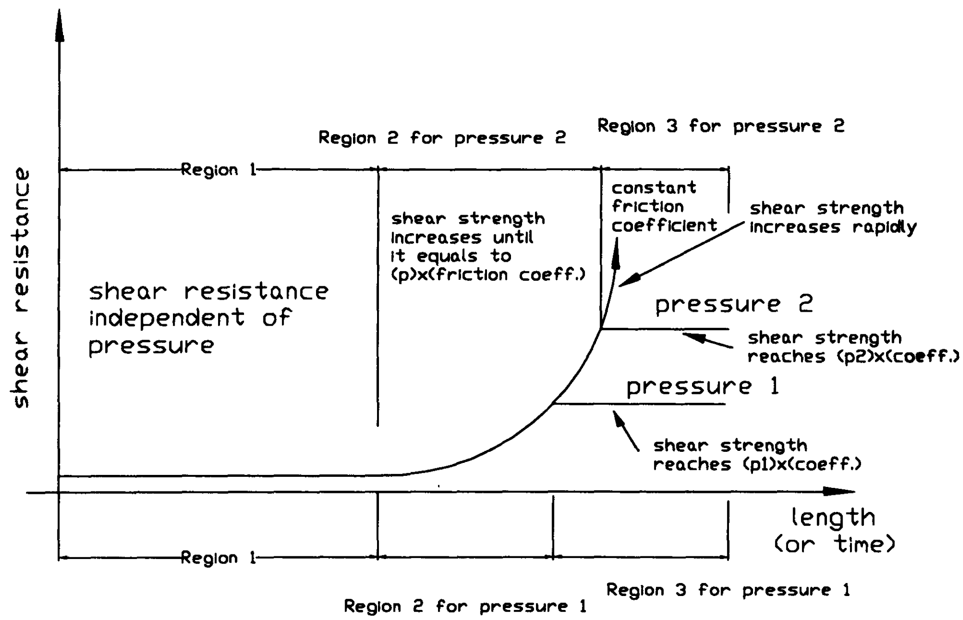


Figure 6-15: New model of the concrete liner

increasing, it will reach the coefficient of friction 0.2-0.27, then there won't be any shear deformation happening, instead, the slipform will start slipping on the surface of the cured concrete.

These two reference experiments are valuable because the setting of the concrete is so slow we can see the transition of concrete from liquid concrete of small shear resistance to liquid concrete of large shear resistance, and then to solid concrete with constant friction coefficient.

6.5 New Model of the Concrete Liner

From the discussions above, we can build up a model of the concrete performance for the CTBM by assuming the concrete chosen will reach its initial set at 1 hour, thus we can rebuild the three region model by the following descriptions as shown in Figure 6-15. The x axis is the shear resistance τ (local friction).

Region 1 Fluid fresh concrete with shear resistance τ=0.1psi which is independent of pressure(by manufacturer's data), x m long.

Region 2 Concrete reaching the initial set, with increasing shear resistance from τ=0.1psi to $\tau = \mu\times$ pressure. y m long, y depends on how high the shear resistance should reach. Simply speaking, Region 2 ends when the shear strenth of cured concrete is stronger enough to withstand the friction force caused by the normal stress. It depends on how high the overburden pressure is and how fast the shear strength can increase.

Region 3 Solid concrete with constant friction coefficient μ. ($\mu = 0.2 - 0.27$), (12-x-y) m long.

For the specific concrete mix of w/c=0.40, s/c=1.30, superplasticizer/c=0.02, and maximum sand size=0.0232in, we can reach the following data from the limited numbers of experiments (test1-4) from Figure 6-12 and Figure 6-13:

- intitial set time=1.25 hr
- speed of shear strength increase τ is 6.94 psi in 15 minutes in test1, and 12.6psi in 25 minutes
- final coefficient of friction is around 0.2-0.27 for solid concrete

6.6 Estimation of Drag Force on the Slipform of the CTBM

By using the three region model built in the last section, we can estimate the friction acting on the slipform of the CTBM by assuming that

- The tunnel is in 100 m deep dense sand.
- The total length of slipform is 12 m with velocity 6 m/hr.
- The circumference of the CTBM is $\pi D = \pi \times 5.4 = 17(m)$.

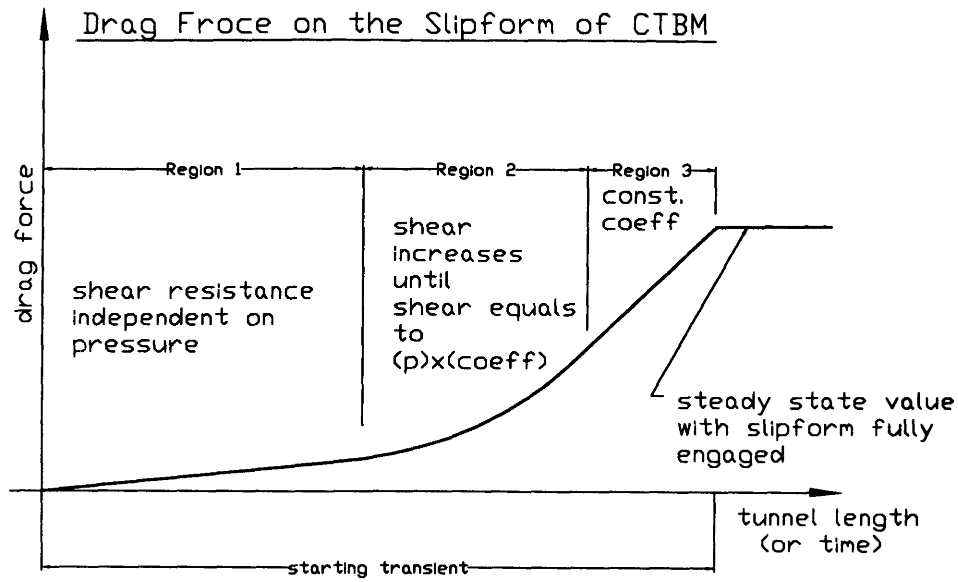


Figure 6-16: Friction Estimation on the CTBM

- Initial set of concrete is at 1.25 hr.
- The overburden pressures on the slipform are 1.5 MPa, 1.5 MPa, and 0.7 MPa in Region 1, 2, and 3 respectively.
- Shear resistance in Region 1 is 0.1 psi, independent of pressure.
- Friction coefficient in Region 3 is 0.27, independent of pressure.
- Shear resistance increase to $p \times \mu$= 0.189 MPa = 27.4psi in 30 minutes

Therefore, we can obtain the result as shown in Figure 6-16, where Region 1 is 7.5m long, Region 2 is 1.8m long, and Region 3 is 2.7m long. The friction estimation is as follows:

$D = 0.1(psi) \times 7.5(m) \times 17(m)$ .... Region 1

$+\frac{0.1+27.4}{2}(psi) \times 1.8(m) \times 17(m)$ ...... Region 2

$+0.27 \times 0.7(MPa) \times 2.7(m) \times 17(m)$ ...... Region 3

$= 20,000(lb) + 652,000(lb) + 1,950,000(lb) = 2,622,000(lb)$

Chapter 7

Conclusions

7.1 Summary

The concept of CTBM shows a way to bore tunnels and to build a continuous liner simultaneously. However, there are some difficulties which need to be overcome. The friction acting on the slipform is one of the major concerns. If CTBM is working on shallow depth or in strong rock, the propulsive force from the concrete can no doubt overcome the friction and provide enough thrust on the cutter head to excavate tunnels. If CTBM is working in 100m deep dense sand, the friction will be too large for it to overcome if there is no other device there to decrease the friction.

The new model of the concrete liner is devised in this thesis project based on the experiments done on the testing apparatus designed and manufactured by ourselves. When we build another three region model, the length of each region should be determined by the knowledge of the property of the concrete and the pressure which will be applied on the slipform.

7.2 Future Work

7.2.1 Building Models of Concrete liners of Different Concrete Mixes

More experiments can be performed to obtain more data about the time of initial setting and the increasing speed of shear strength τ of different concrete mixes. Each test takes 2-5 hours to finish, which depends on the different mixes of concrete.

7.2.2 Solving the Friction Problem

The friction may be bigger than the propulsive thrust provided by pumped concrete. It needs to be solved by other methods like lubrication. Similar tests with the lubricating function can be performed in the existing testing apparatus by changing the design of some parts of the machine.

Furthermore, the curing of concrete is very important for its quality. Usually, once the concrete reaches its initial set, no disturbances should be allowed. The designers should take it into consideration while designing the methods to decrease the friction.

7.2.3 Solving the Lip Seal Problem

The other major concern of CTBM is the seal problem. Since the tunnels bored are not perfectly round, there will be leakage if the lip seal is not working well, and the pumped concrete will be extruded out from the leakage. Once it flows to the cutter head, it may stick on the cutters and cause damage. The lip seal in the conceptual design is a flexible mechanism but its performance is not yet proven. Some other methods should be discovered to solve the seal problem. One possible way is to pump foams or other materials into the clearance between

CTBM to build a natural seal. In the future research, the details should be taken into consideration to guarantee no leakage under any situation.

Appendix A

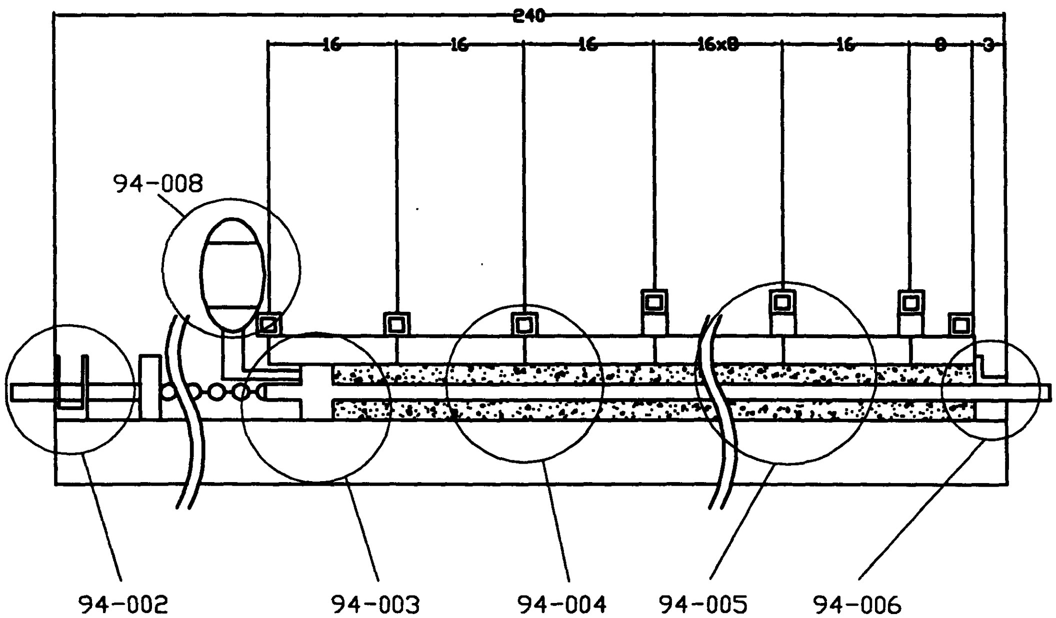
Parts of the Testing Apparatus

PARTS OF THE TESTING APPARATUS					
No.	Name	QTY	Material	Drawing	Remarks
1	thrust bearing	1	copper		Din=3/4"
2	power screw support	1	steel	94-010	channel 3"x1.41", t=0.17", l=4"
3	power screw	1	steel		3/4-10 screw, l=24"
4	1/2 bolt	32	steel		1/2-13 bolt, l=1.5"
5	pull block	1	steel	94-011	
6	load cell connector	2	steel		1/2-20 screw, l=1.5"
7	1/2 long bolt	2	steel		1/2-13 bolt, l=3"
8	1/2 nut	34	steel		
9	air source connector	1			
10	top cap	1	cast iron	94-012	2" pipe cap
11	concrete container	1	cast iron		2" pipe, l=8"
12	bottom cap	1	cast iron	94-012	2" pipe cap
13	1/4 pipe nipple	4	steel		1/4" pipe, l=1.5"
14	air pressure gauge	1			rated 100psi
15	pumping pipe	1	copper		3/8"pipe, l=25", bended, thread both ends
16	3/8" pull pin	1	steel		d=3/8", l=1"
17	pull plate	2	steel	94-013	9/8"x1/8", l=25"
18	pumping head	1	steel	94-014	
19	1/4" pull pin	2	steel		d=1/4", l=9/8"
20	1/8" spring pin	2			d=1/8", l=1"
21	short column	10	steel		3/4-10 screw, l=5.5"
22	top beam	15	steel	94-015	1" square pipe, l=4"
23	short column cover	10	steel		3/4 schedule 40 pipe, l=2.25"
24	left angle	1	steel	94-016	angle 1.5"x1.5", t=1/8", l=209"
25	testing base	1	steel	94-016	channel 5"x1.75", t=0.19", l=240"
26	pressure press	13	steel		1" square pipe, l=16"
27	slipform	1	steel	94-017	1"x1/8", l=200"
28	3/4 nut	65	steel		3/4-10 nut
29	wire	1	iron		d=1/16"
30	right angle	1	steel	94-016	angle 1.5"x1.5", t=1/8", l=209"
31	first pressure press	1	steel		1" square pipe, l=8"
32	long column	20	steel		3/4-10 screw, l=7"
33	long column cover	20	steel		3/4 schedule 40 pipe, l=3 25/32
34	pressure pad	25	steel		1.4"x2"x0.25"
35	hydraulic cylinder	10			made by ENERPAC, rated 5 tons
36	set screw	2	steel		1/4-20 set screw
37	union	3	cast iron		1/4 NPT female-1/2 NPT male

38	valve	2			1/2 NPT female on both ends, rated 400psi
39	motor with controller	1			reated 1/8 hp
40	T fitting	2	cast iron		1/4 NPT
41	high pressure hose	10			made by ENERPAC, rated 10 kpsi
42	high pressure elbow	1			made by ENERPAC, rated 10 kpsi
43	high pressure T fitting	10			made by ENERPAC, rated 10 kpsi
44	3/8 seamless pipe	11	steel		schedule 80, l=16", thread both ends
45	high pressure gauge	1			rated 10 kpsi
46	hydraulic pump	1			made by ENERPAC, rated 10 kpsi
47	start angle	1	steel	94-018	angle 2"x2", t=1/8", l=4"
48	shaft connector	1	Al.	94-020	
49	start opening	2	steel	94-018	1.5"x2"x3/8"
50	start base	1	steel	94-018	4"x2"x1/2"
51	Aluminum pad	1	Al.		1.5"x2"x1/4"
52	load cell	1			rated 0 - 2000 lbs.
53	chain connector	1	steel	94-019	
54	chain hook	1	steel		
55	chain	1	steel		l=240"
56	driving sprocket	1	steel		made by SDP, pitch 0.353, teeth 8
57	ladder chain	1	HTS		made by SDP, pitch 0.353, l=3 ft
58	driven sprocket	1	steel	94-021	made by SDP, pitch 0.353, teeth 80
59	C ring	4			1/4"

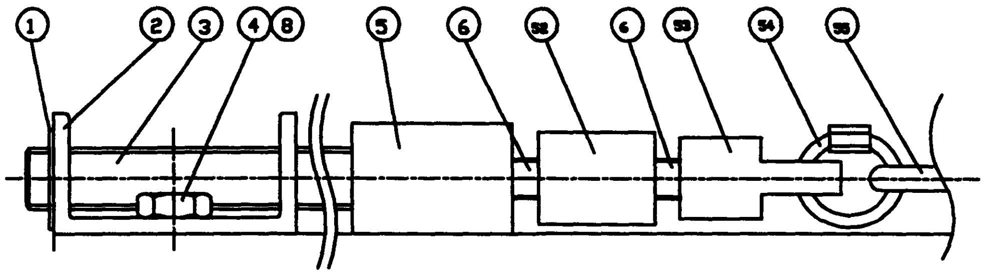
Appendix B

Design Drawings of the Testing Apparatus



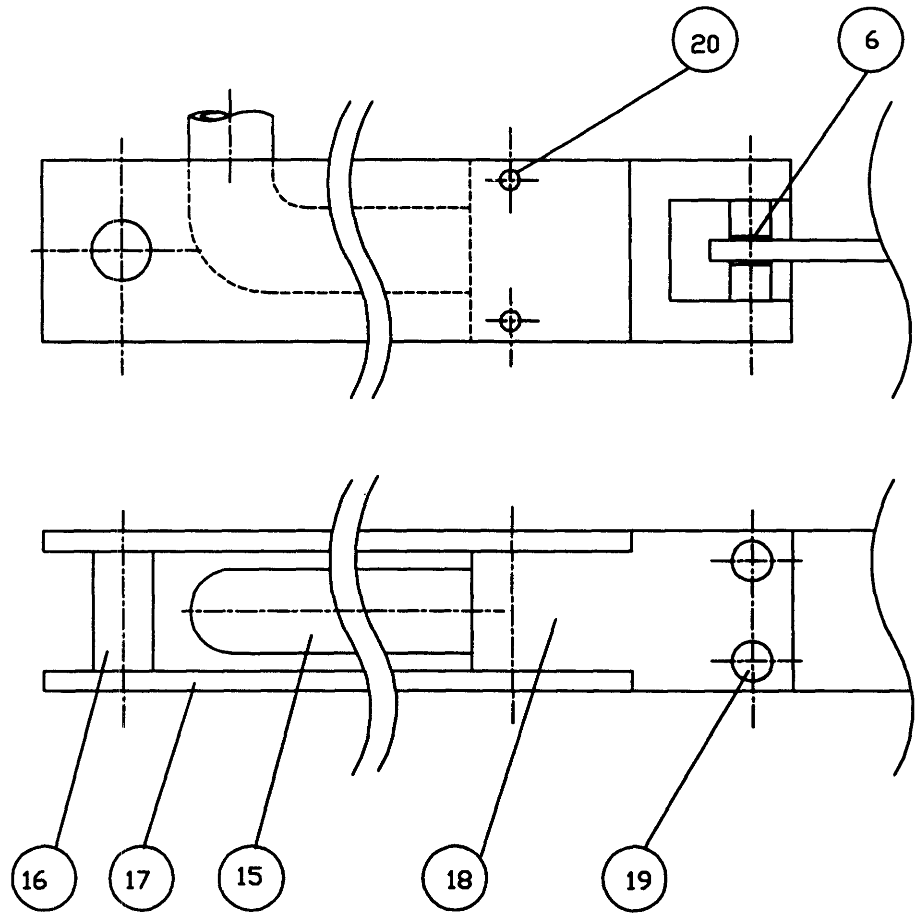
Note: This drawing is not on scale, it is drawn to show the relative positions of the parts in this machine

M.I.T. Mechanical Engineering Dep.			
drawing name	total assembly		
designer	Ming-chihWeng	scale	
date	Apr.'94	drawing no.	94-001



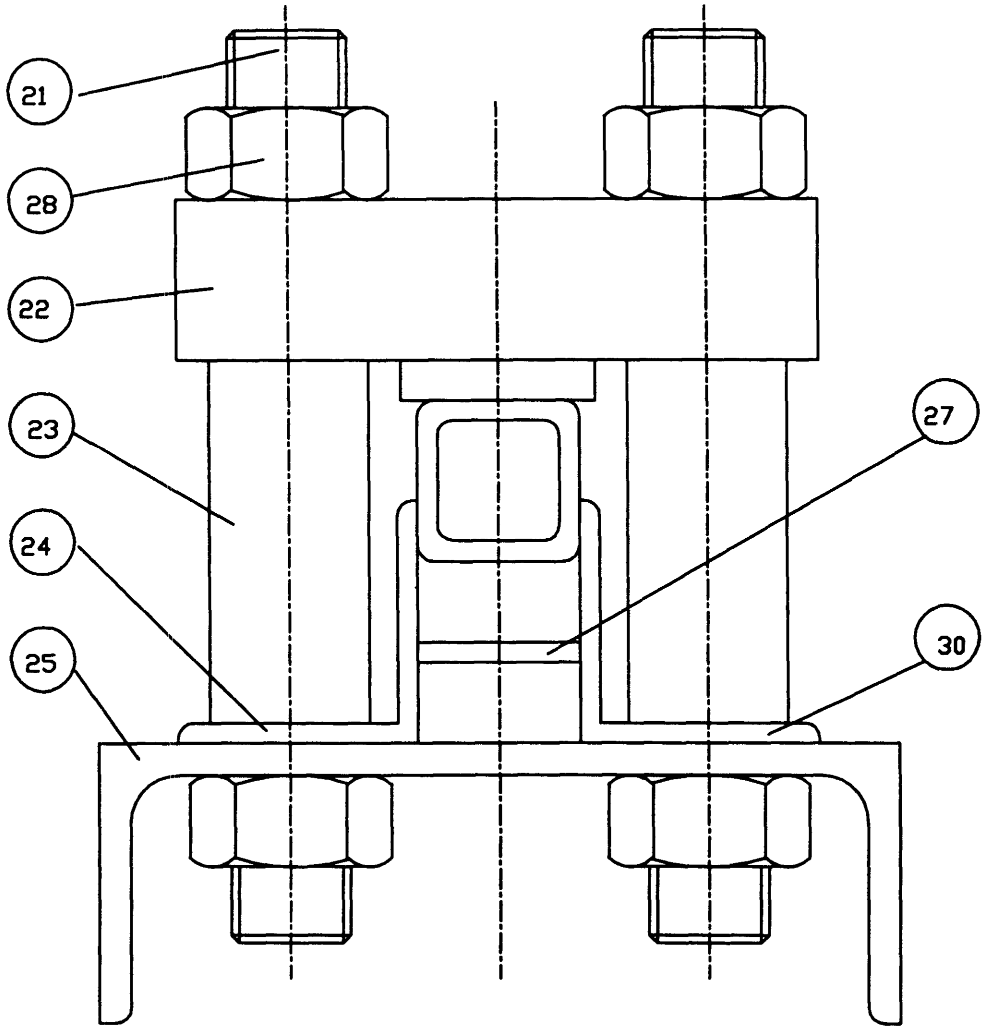
no.	part name	QTY	remarks
55	chain	1	240"long
54	chain hook	1	
53	chain pull	1	
52	load cell	1	rated 2klb
8	1/2 in nut	32	
6	1/2-20	2	
5	pull block	1	
4	1/2in bolt	32	
3	pull screw	1	
2	support	1	
1	bearing	1	copper

M.I.T. Mechanical Engineering Dep.			
drawing name	driving system		
designer	Ming-chihWeng	scale	1:2
date	Apr.'94	drawing no.	94-002



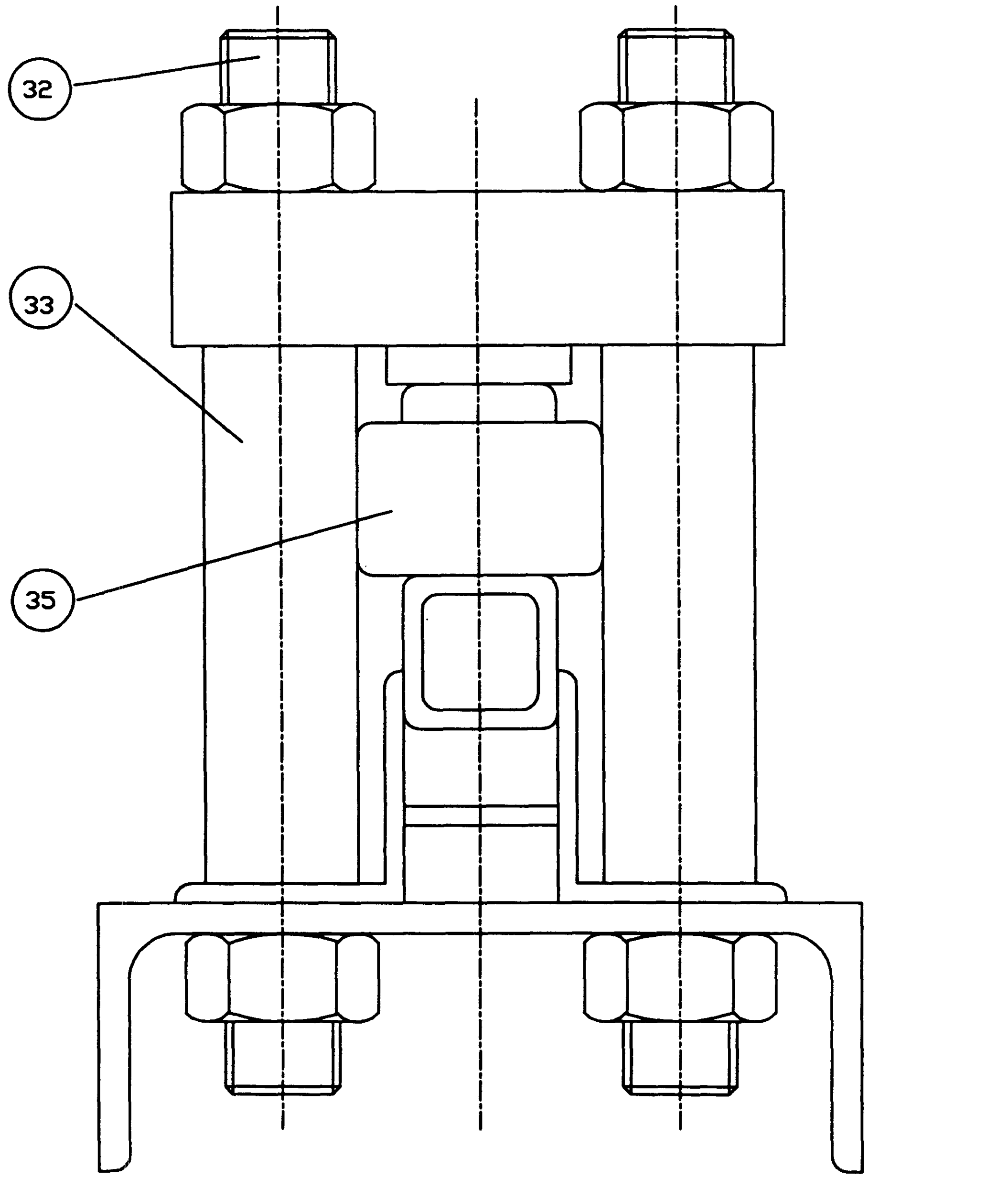
20	spring pin	2	1/8"dia,l=1"
19	pin	2	1/4"dia,l=1.125
18	head	1	
17	pull plate	2	
16	pull pin	1	3/8" dia
15	pipe	1	3/8"pipe
59	C ring	4	
no.	n a m e	QTY	remarks

M.I.T. Mechanical Engineering Dep.			
drawing name	pumping head		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-003

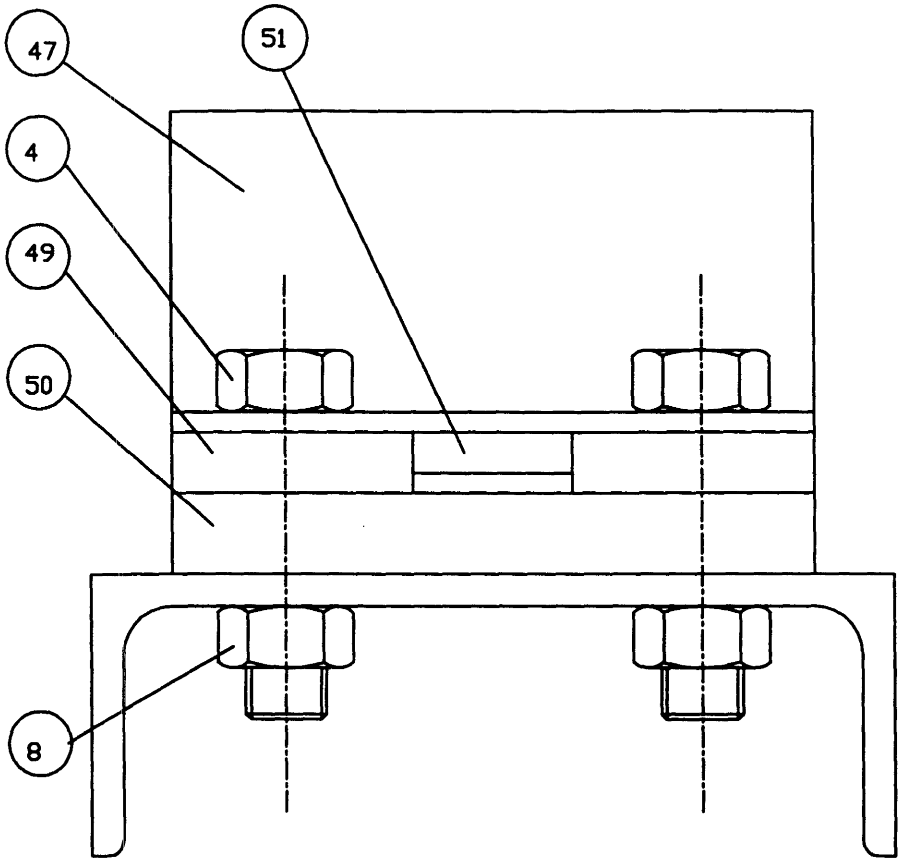


no.	n a m e	QTY	remarks
30	angle-R	1	1.5′angle
28	3/4′ nut	65	
27	slipform	1	1′x1/8′ steel
25	base	1	5′ channel
24	angle-L	1	1.5′ angle
23	cover-s	10	3/4 in pipe
22	top beam	15	1 in square
21	column-s	10	3/4 in screw

M.I.T. Mechanical Engineering Dep.			
drawing name	structure 1		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-004

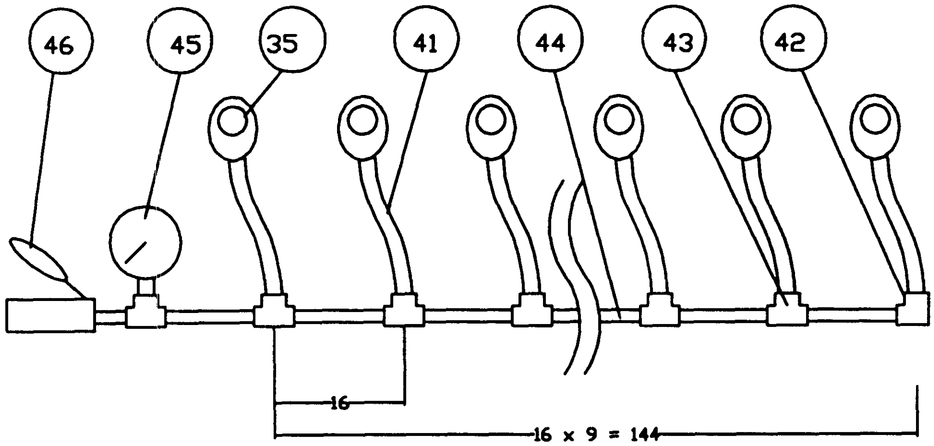


35	jack	10	rated 5 tons
33	cover	20	3/4 pipe
32	column	20	3/4in screw
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	structure 2		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-005



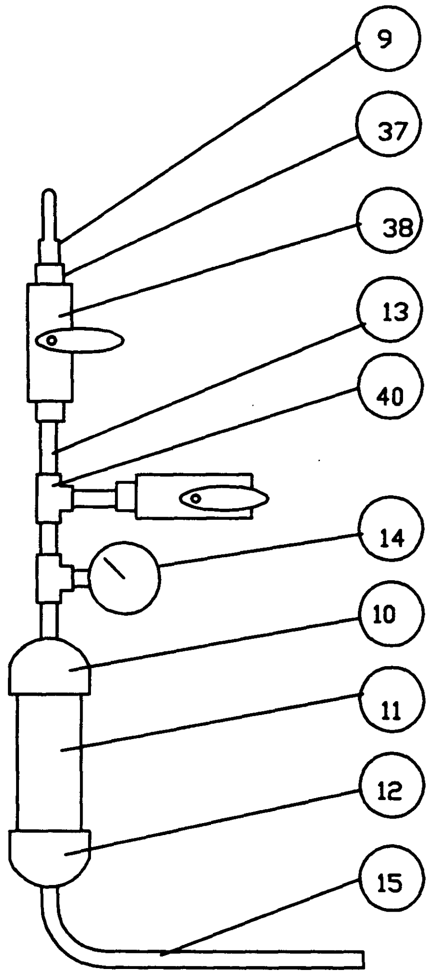
51	Al pad	1	Al
50	startbase	1	
49	opening	2	
47	angle	1	2"x1/8"angle
8	1/2" nut	32	
4	1/2" bolt	32	
no.	n a m e	QTY	remarks

M.I.T. Mechanical Engineering Dep.			
drawing name	begin base		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-006



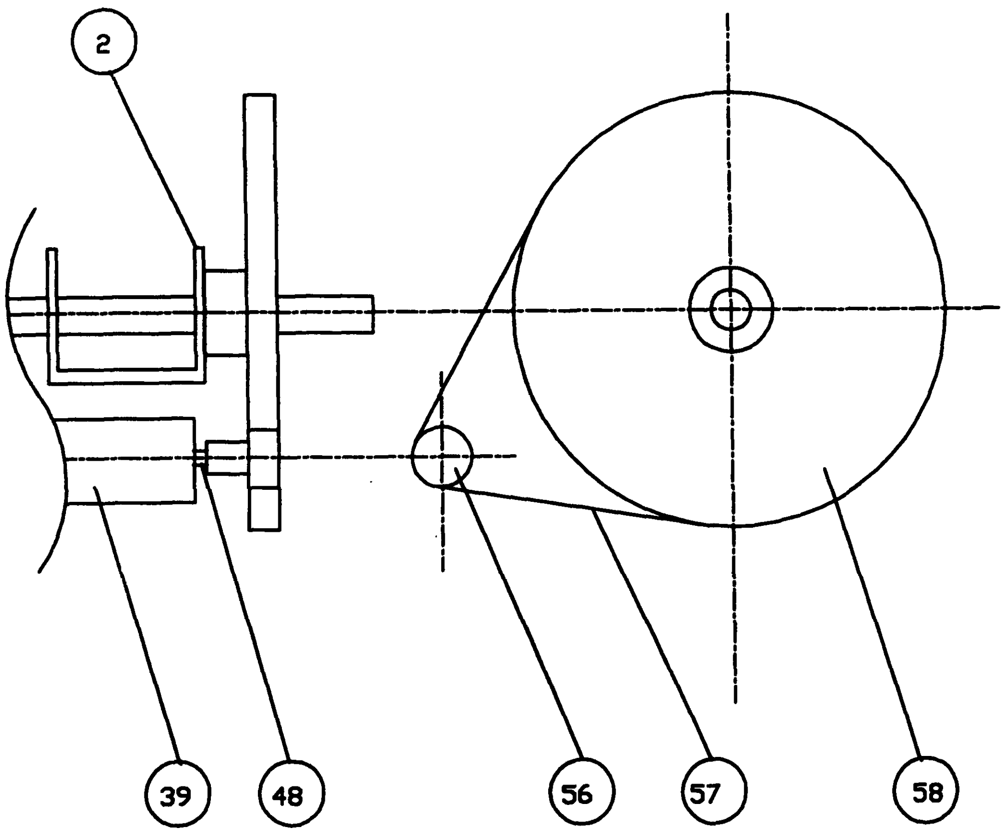
Note: This drawing is not on scale. It is drawn to show the relative positions of the parts in this machine.

46	pump	1	rated 10kpsi
45	gauge	1	rated 10kpsi
44	oil pipe	11	3/8'seamless
43	tee	10	rated 10kpsi
42	elbow	1	rated 10kpsi
41	hose	10	rated 10kpsi
35	jack	10	rated 5 tons
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	hydraulic system		
designer	Ming-chihWeng	scale	
date	Apr.'94	drawing no.	94-007

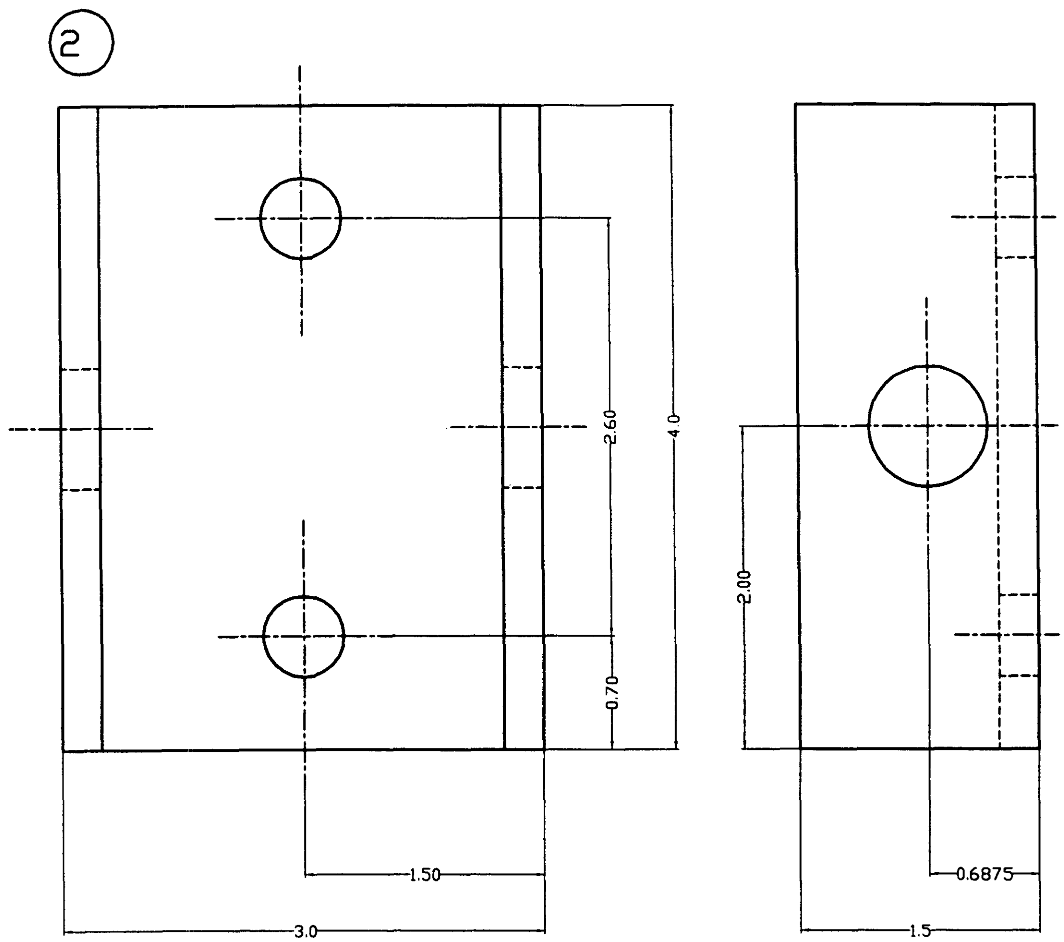


no.	name	QTY	remarks
40	Tee	2	1/4"
38	valve	2	1/2"threading
37	union	3	1/4" to 1/2"
15	pipe	1	copper
14	gauge	1	rated 100psi
13	nipple	4	1/4"
12	bottomcap	1	2"cap
11	container	1	2"pipe
10	top cap	1	2"cap
9	connector	1	

M.I.T. Mechanical Engineering Dep.			
drawing name	regulator system		
designer	Ming-chihWeng	scale	
date	Apr.'94	drawing no.	94-008

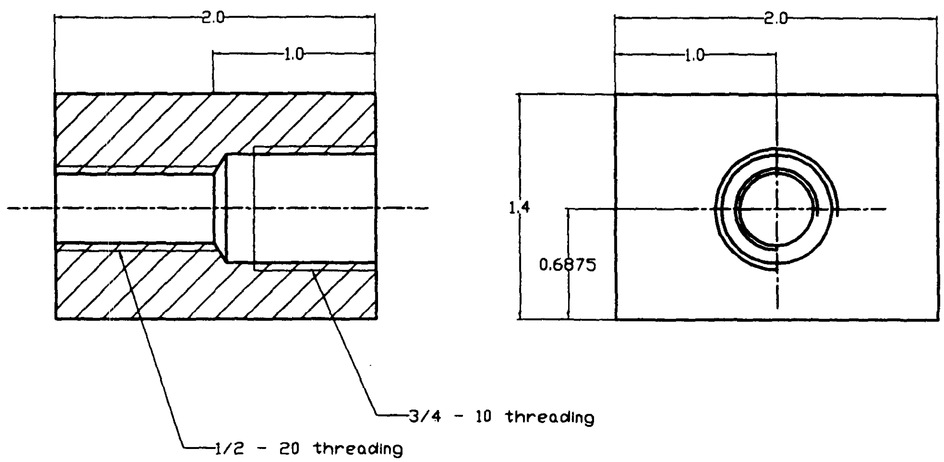


58	sprocket	1	80 teeth
57	chain	1	
56	sprocket	1	8 teeth
48	shaft	1	
39	motor	1	
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	speed reducer		
designer	Ming-chihWeng	scale	
date	Apr.'94	drawing no.	94-009

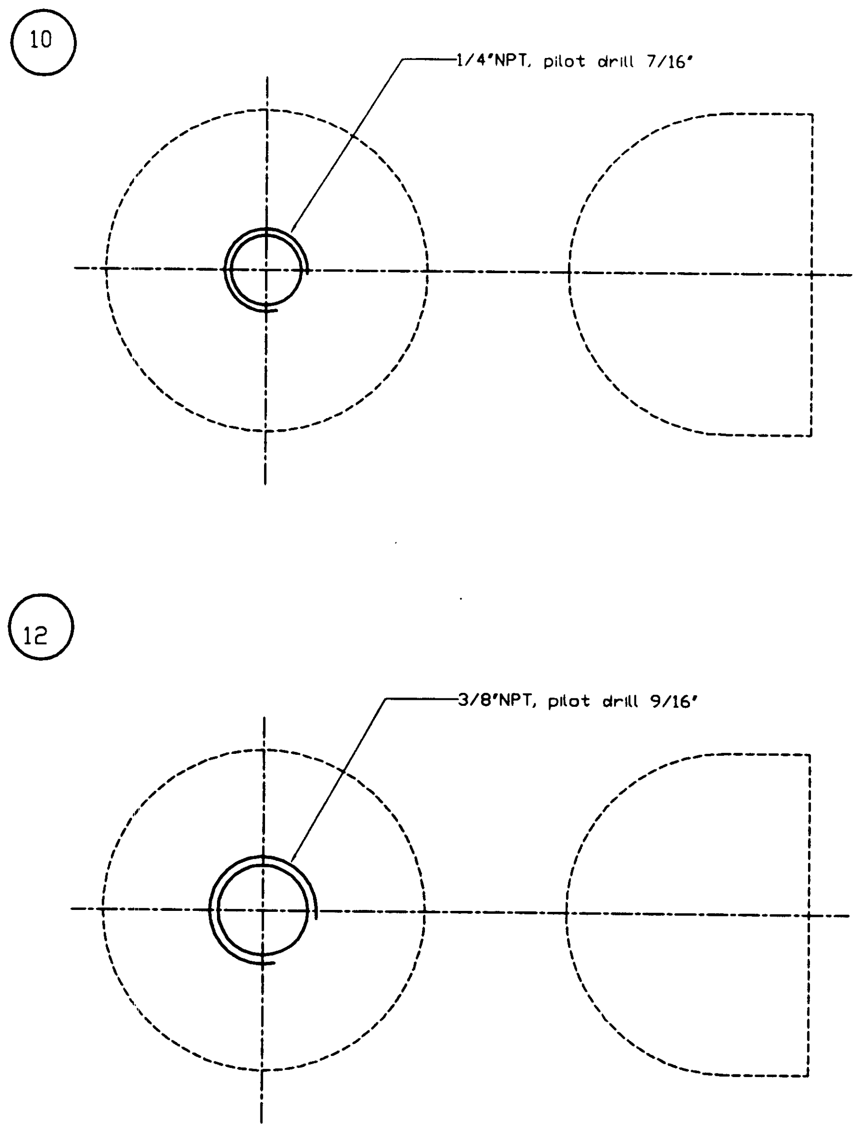


2	support	1	3"x1.5"channel	
no.	n a m e	QTY	remarks	
M.I.T. Mechanical Engineering Dep.				
drawing name	screw support			
designer	Ming-chihWeng	scale	1:1	
date	Apr.'94	drawing no.	94-010	

5



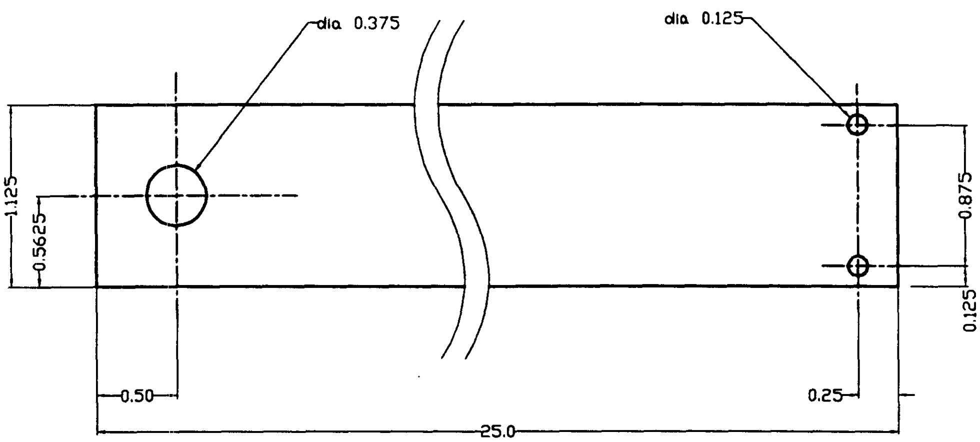
5	pull block	1	
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	pull block		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-011



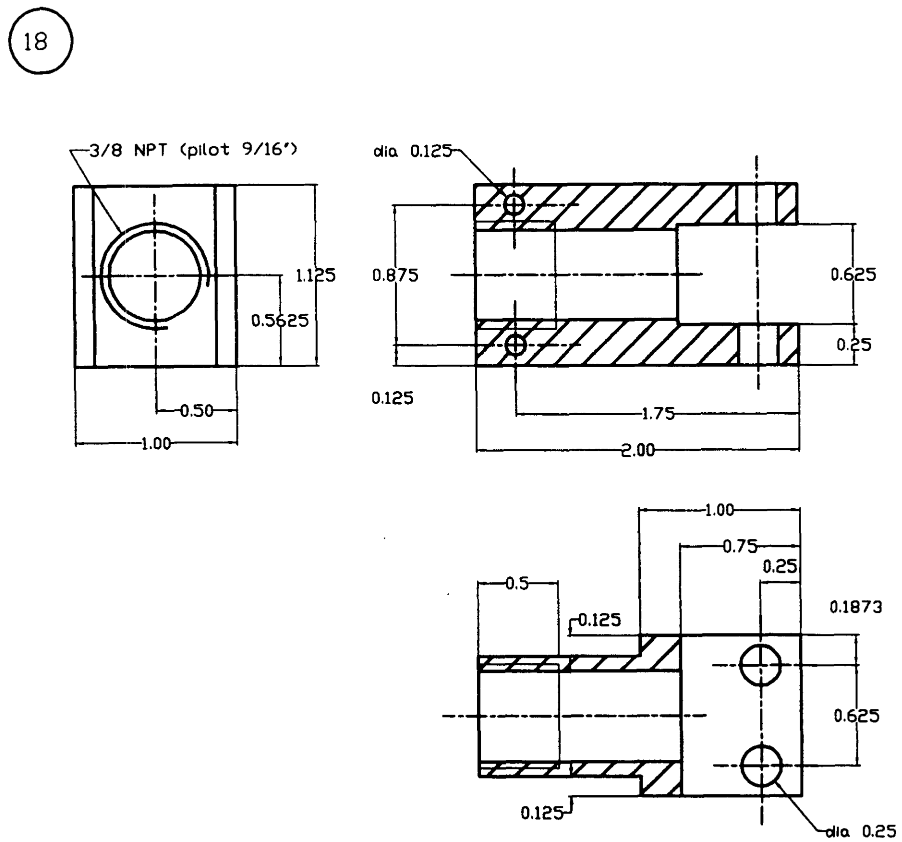
12	bottomcap	1	2" cap		
10	top cap	1	2" cap		
no.	n a m e	QTY	remarks		
M.I.T. Mechanical Engineering Dep.					
drawing name		container caps			
designer	Ming-chihWeng		scale	1:1	
date	Apr.'94	drawing no.	94-012		

17

thinkness = 1/8'

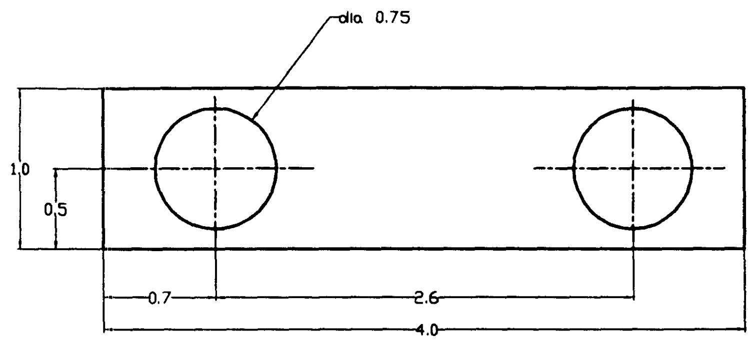


17	pull plate	2	
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	pull plate		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-013



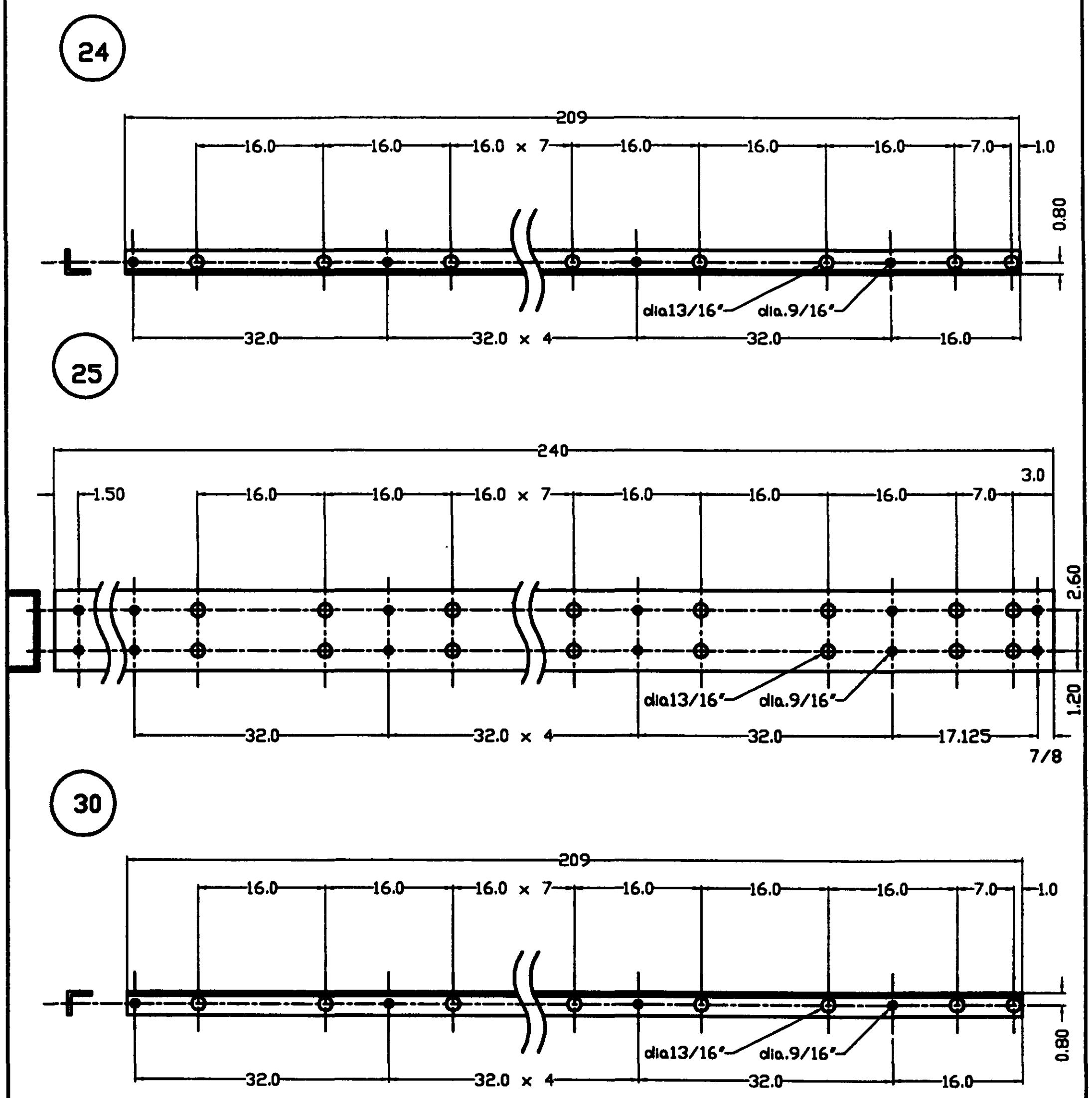
18	head	1	
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	pumping head		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-014

22



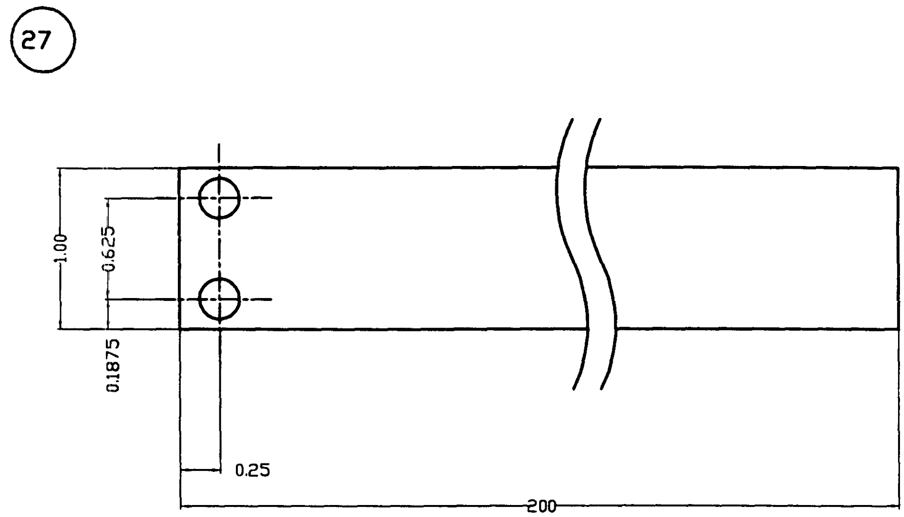
material: 1"x1" square pipe

22	top beam		15	1' square	
no.	n a m e		QTY	remarks	
M.I.T. Mechanical Engineering Dep.					
drawing name			top beam		
designer	Ming-chihWeng			scale	1:1
date	Apr.'94		drawing no.	94-015	

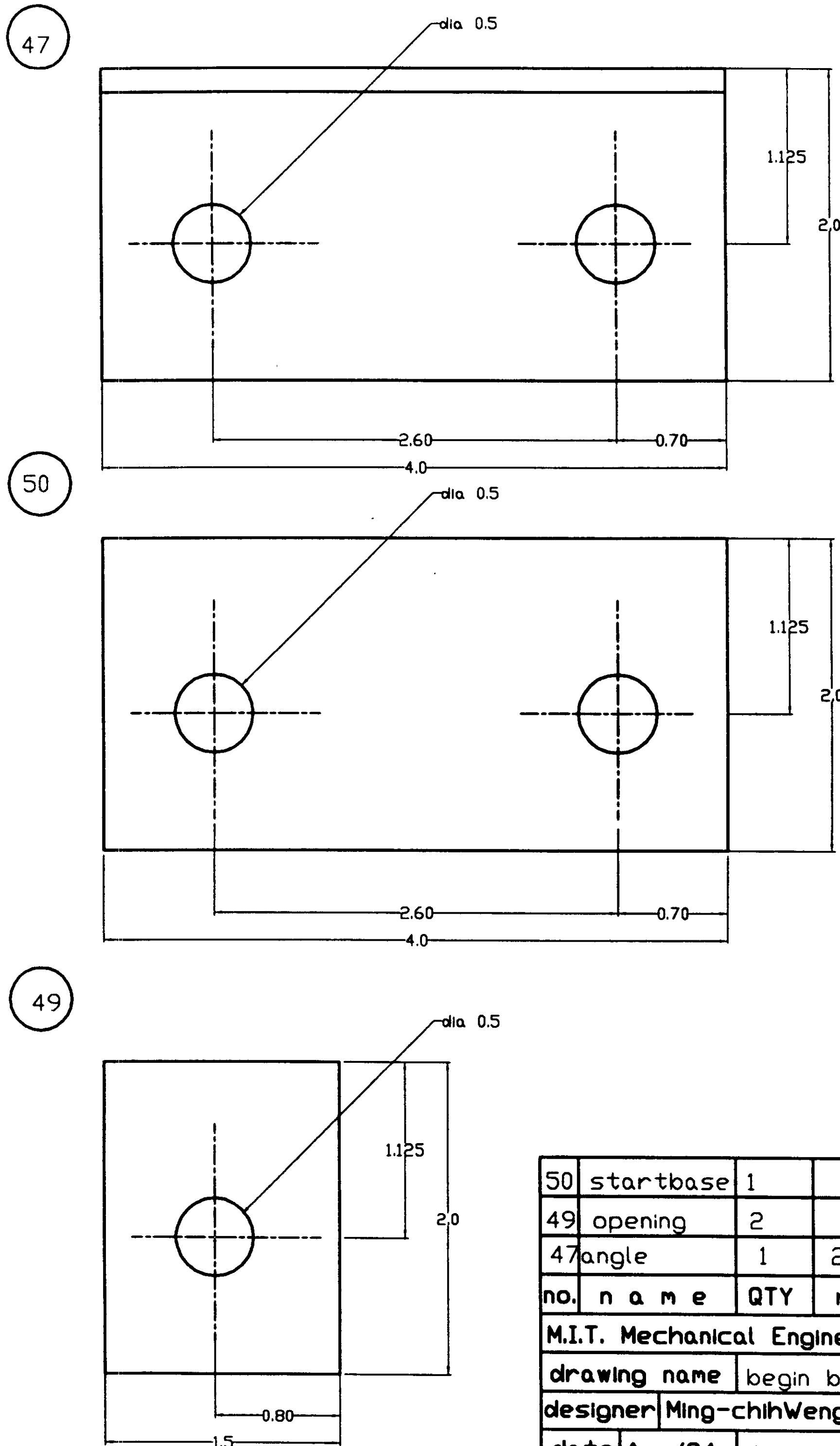


1. this drawing is not drawn on scale.
2. these 3 parts have similar features and will be assembled together

30	angle - R	1	1.5" angle
25	base	1	5" channel
24	angle - L	1	1.5" angle
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	testing base		
designer	Ming-chihWeng	scale	
date	Apr.'94	drawing no.	94-016

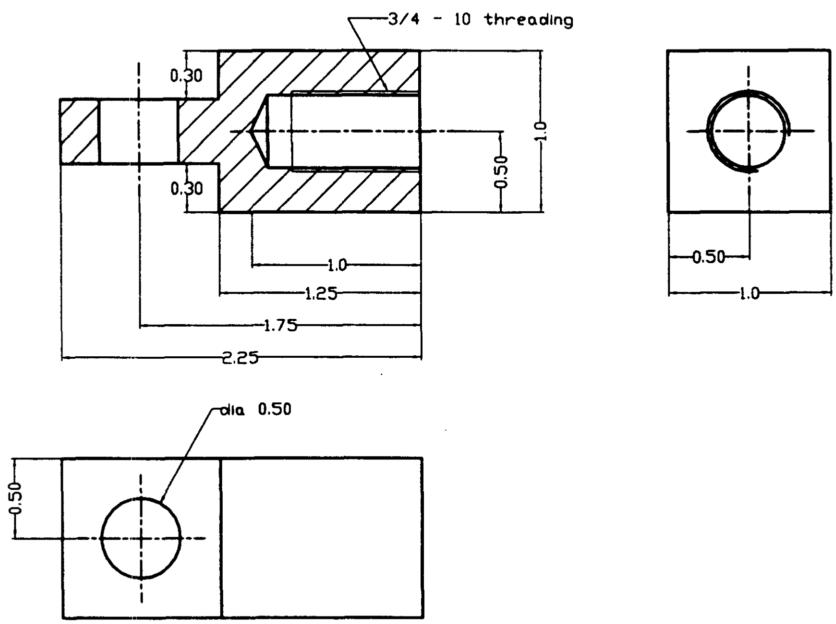


27	slipform	1	1"x1/8"steel
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	slipform		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-017

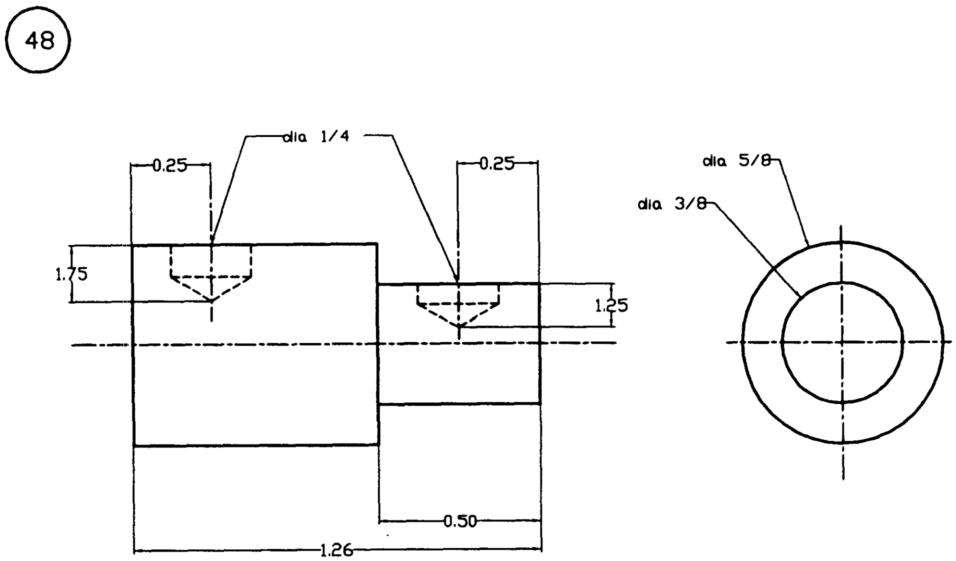


50	startbase	1	
49	opening	2	
47	angle	1	2"x1/8"angle
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	begin base		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-018

53

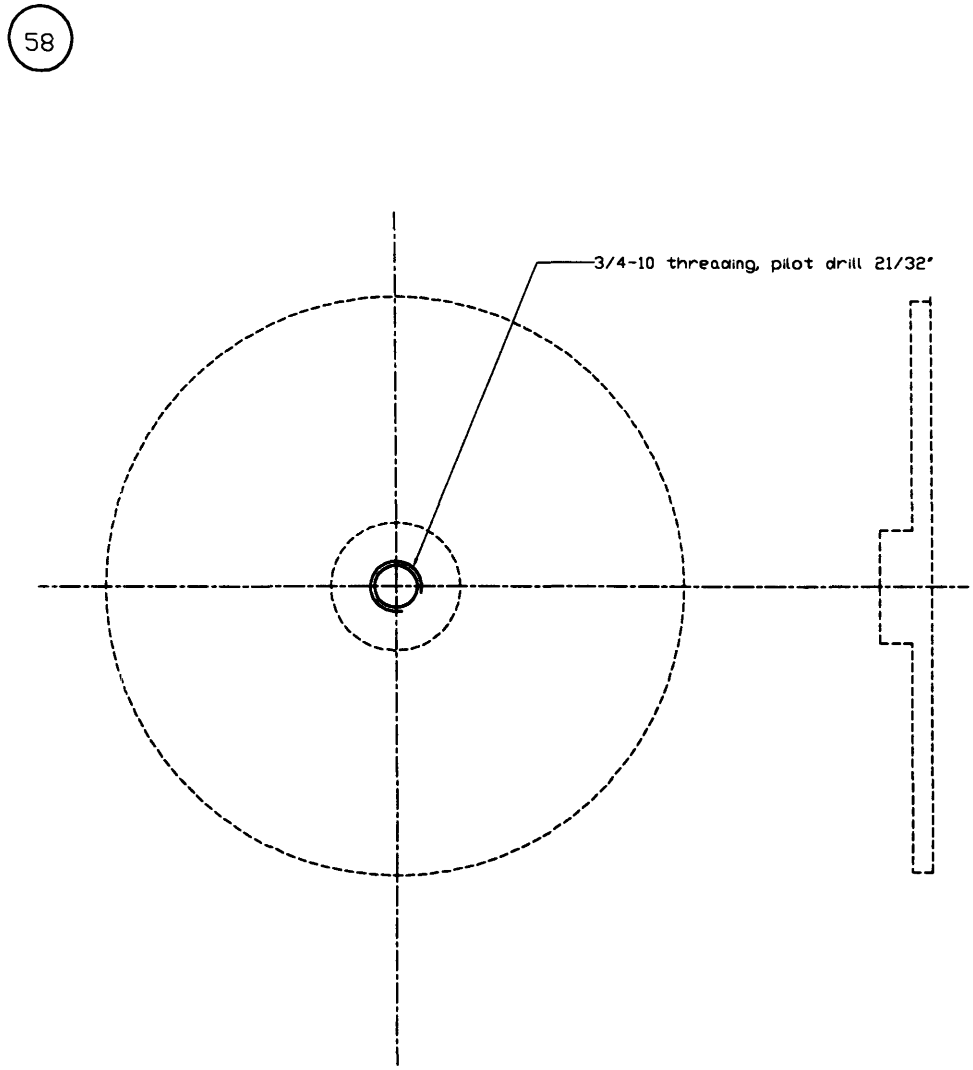


53	chain pull	1	
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	chain connector		
designer	Ming-chihWeng	scale	1:1
date	Apr.'94	drawing no.	94-019



material : Aluminum

48	shaft	1	
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	shaft connector		
designer	Ming-chihWeng	scale	2:1
date	Apr.'94	drawing no.	94-020



58	sprocket	1	80 teeth
no.	n a m e	QTY	remarks
M.I.T. Mechanical Engineering Dep.			
drawing name	driven sprocket		
designer	Ming-chihWeng	scale	
date	Apr.'94	drawing no.	94-021

Appendix C

Calculations of the design

C.1 Speed Reducer

C.1.1 Power Screw Stress Analysis

The force calculation of the power screw system is based on the pulling force of 2.000 lbs. At first we look at the stress acting on the screw rod:

The average shear stress on the screw rod

$$\tau_1 = \frac{2F}{\pi d_r h}$$

The average shear stress on the nut (driven sprocket)

$$\tau_2 = \frac{2F}{\pi d h}$$

The average bearing stress on the screw

$$\sigma = \frac{4F}{\pi h(d^2 - d_r^2)N}$$

where

$\sigma_{yield} = 50kpsi$

$F = 2000lbs$

$d = 0.75in$

$d_r = 0.627in$

$N = 10threads/in$

$h = 13/16in$

so

$\tau_1 = 2500psi$

$\tau_2 = 2100psi$

$\sigma = 1850psi$

The stress analysis proves that the screw rod of 3/4-10 is very safe for the usage of the load of 2000lbs. Assume the yielding strength is 60kpsi, the safty factor is almost 20.

C.1.2 Power Screw Torque Analysis

Neglecting the friction on the thrust bearing, the torque T needed to drive a load by a screw rod is

$T_{ideal} = \frac{Fl}{2\pi}$

$T_{real} = \frac{Fd_m}{2}\left(\frac{l+\pi\mu d_m sec\alpha}{\pi d_m - \mu l sec\alpha}\right)$

where

$F = 2000lbs$

$d_m = 0.685in$

$\mu = 0.08$

$l = pitch = 1/10in$

$\alpha = 30^o$

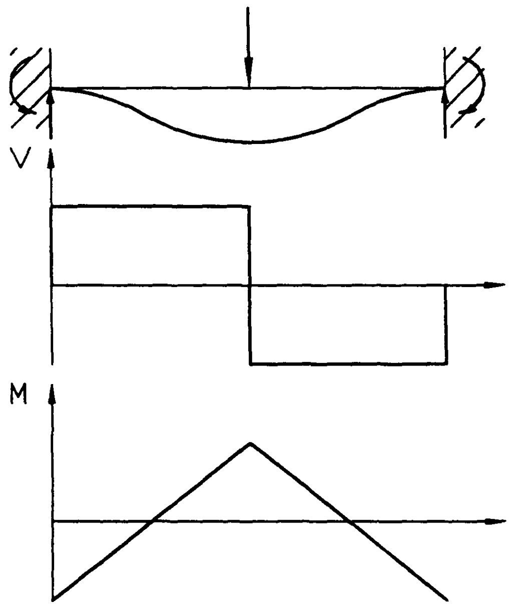


Figure C-1: Stress analysis of the 3/8" pin

so

$T_{ideal} = 32in - lbs$

$T_{real} = \frac{2000\times0.685}{2}(\frac{0.1+\pi\times0.3\times0.6875sec30^{o}}{\pi\times0.6875-0.3\times0.1sec30^{o}})$

$T_{real} = 95in - lbs$

efficiency $\eta = \frac{T_{ideal}}{T_{real}} = 32/95 = 34\%(\mu = 0.08)$

C.2 Concrete Pumping System

C.2.1 Choosing the 3/8" pins

For the 3/8" pin which is made of cold drawn steel ($\sigma_{yield} = 60kpsi$), we should consider shear stress and bending stress as well. For the pulling plate made of cold drawn steel. we should consider tension stress and bearing stress as well.

For the 3/8" pin

(refer to Figure C-1)

$\tau_{shear} = \frac{V}{A}$

$\sigma_{bending} = \frac{My}{I}$

$\sigma_{combined} = \sqrt{\sigma_{bending}^2 + 3\tau_{shear}^2}$

where

$V = 1000lbs$

$A = \frac{\pi d^2}{4} = 0.11in^2$

$M = \frac{Fx}{4} = \frac{2000\times0.375}{4} = 188in - lb$

$I = \frac{\pi d^4}{64} = 9.71 \times 10^{-4}in^4$

so

$\tau_{shear} = \frac{1000}{0.11} = 9090psi$

$\sigma_{bending} = \frac{188\times0.1875}{9.71\times10^{-4}} = 36300psi$

$\sigma_{combined} = \sqrt{36300^2 + 3 \times 9090^2} = 40000psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{combined}} = 1.5$

For the pulling plate connectted with the 3/8" pin

$\sigma_{tension} = \frac{V}{A_{cross}}$

$\sigma_{bearing} = \frac{V}{A_{bearing}}$

where

$V = 1000lbs$

$A_{cross} = Thickness \times (Width - Diameter_{pin}) = (1/8) \times (3/4) = 0.094in^2$

$A_{bearing} = Thickness \times Diameter_{pin} = (1/8) \times (3/8) = 0.047in^2$

so

$\sigma_{tension} = 10,600psi$

$\sigma_{bearing} = 21,300psi$

$N_{safety} = \frac{sigma_{yield}}{\sigma_{max}} = \frac{60000}{21300} = 2.8$

C.2.2 Choosing the 1/8" pin

For the 1/8" spring pins, we can use the rated shear load from the catalog since there is no bending stress in these parts. The rated load for spring pins 1/8" is 633 kgw (1400 lbs) [5]. For the pulling plate made of cold drawn steel, we should consider shear stress and bearing stress as well.

For the 1/8" spring pins

$$N_{safety} = \frac{RatedLoad}{RealLoad} = \frac{1400lbs}{500lbs/pin} = 2.8$$

For the pulling plate connectted with the 1/8" pin

$\sigma_{tension} = \frac{V}{A_{cross}}$

$\sigma_{bearing} = \frac{V}{A_{bearing}}$

where

$V = 500lbs$

$A_{cross} = Thickness \times (Width - Diameter_{pin}) = (1/8) \times (1) = 0.125in^2$

$A_{bearing} = Thickness \times Diameter_{pin} = (1/8) \times (1/8) = 0.0156in^2$

so

$\sigma_{tension} = 4,000psi$

$\sigma_{bearing} = 32,000psi$

$N_{safety} = \frac{sigma_{yield}}{\sigma_{max}} = \frac{60000}{32000} = 1.9$

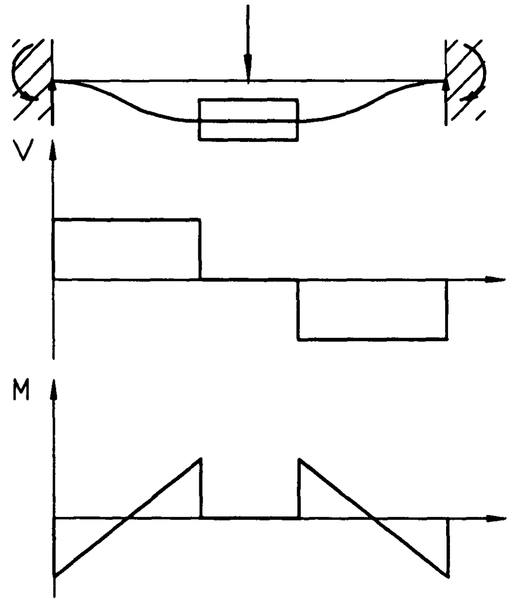


Figure C-2: Stress anylysis of the 1/4" pin

C.2.3 Choosing the 1/4" Pin

For the 1/4" pins which are made of cold drawn steel ($\sigma_{yield} = 60kpsi$), we should consider the shear stress and the bending stress as well. For the slipform which is made of hot rolled steel ($\sigma_{yield} = 50kpsi$), we should consider the tension stress and bearing stress as well.

For the 1/4" pins

(refer to Figure C-2)

$\tau_{shear} = \frac{V}{A}$

$\sigma_{bending} = \frac{My}{I}$

$\sigma_{combined} = \sqrt{\sigma_{bending}^2 + 3\tau_{shear}^2}$

where

$V = 500lbs$

$A = \frac{\pi d^2}{4} = 0.049in^2$

$M = \frac{Fx}{4} = \frac{1000 \times 0.25}{4} = 62.5in - lb$

$I = \frac{\pi d^4}{64} = 1.92 \times 10^{-4} in^4$

so

$\tau_{shear} = \frac{500}{0.049} = 10200psi$

$\sigma_{bending} = \frac{62.5 \times 0.125}{1.92 \times 10^{-4}} = 40700psi$

$\sigma_{combined} = \sqrt{40700^2 + 3 \times 10200^2} = 44400psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{combined}} = 1.35$

For the slipform connectted with the 1/4" pin

$\sigma_{tension} = \frac{F}{A_{cross}}$

$\sigma_{bearing} = \frac{F/2}{A_{bearing}}$

where

$F = 2000lbs$

$A_{cross} = Thickness \times (Width - Diameter_{pin}) = (1/8) \times (1/2) = 0.0625in^2$

$A_{bearing} = Thickness \times Diameter_{pin} = (1/8) \times (1/4) = 0.0312in^2$

so

$\sigma_{tension} = 32,000psi$

$\sigma_{bearing} = 32,000psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{max}} = \frac{60000}{32000} = 1.9$

C.3 Ground Pressure Simulating System

C.3.1 Top Beam Stress Analysis

For the top beam (similar to the 1/4" pin calculation):

$\tau_{shear} = \frac{V}{A}$

$\sigma_{bending} = \frac{My}{I}$

$\sigma_{combined} = \sqrt{\sigma^2_{bending} + 3\tau^2_{shear}}$

where

$V = 1.2tons = 2400lbs$

$A = w^2_{outside} - w^2_{inside} = 0.438in^2$

$M = \frac{Fx}{4} = \frac{2400 \times 0.425}{4} = 255in - lb$

$I = \frac{w^4_{outside} - w^4_{inside}}{12} = 0.057in^4$

so

$\tau_{shear} = \frac{2400}{0.438} = 5500psi$

$\sigma_{bending} = \frac{255 \times 0.5}{0.057} = 2200psi$

$\sigma_{combined} = \sqrt{2200^2 + 3 \times 5500^2} = 9800psi$

$N_{safety} = \frac{\sigma_{yield}}{\sigma_{combined}} = 5.1$

C.3.2 Pressure Press Stress Anylysis

(refer to Figure C-3)

$\tau_{shear} = \frac{V}{A}$

$\sigma_{bending} = \frac{My}{I}$

where

$V = 1.2tons = 2400lbs$

$p = 300lbs/in$

$A = w^2_{outside} - w^2_{inside} = 0.438in^2$

$M = \frac{px(l-x)}{2} = \frac{300 \times 7 \times 7}{2} = 7350in - lb$

$I = \frac{w^4_{outside} - w^4_{inside}}{12} = 0.057in^4$

so

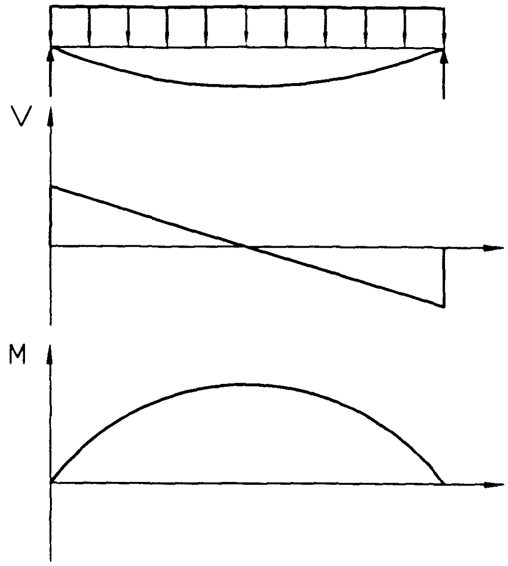


Figure C-3: Stress analysis of the pressure press beam

$\tau_{shear} = \frac{2400}{0.438} = 5500psi$

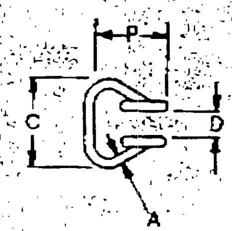
$\sigma_{bending} = \frac{7350 \times 0.5}{0.057} = 64000psi$

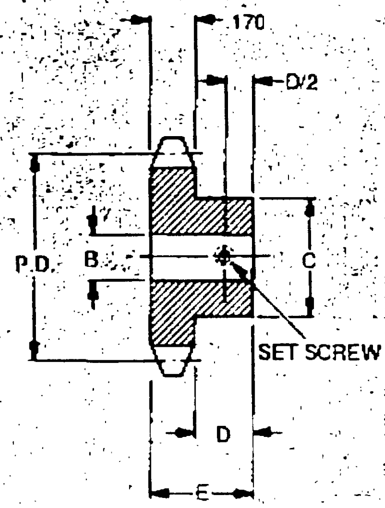
$N_{safety} = \frac{\sigma_{yield}}{\sigma_{max}} = 1.1$

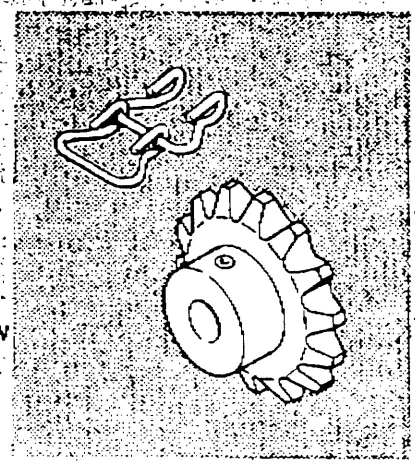
Appendix D

Specifications of Commercial Parts

■ SIZE 14 ■ STEEL ■ .170 FACE







LADDER CHAIN

Priced Per Foot

Catalog Number	Material	P Pitch	Links Per Foot	A Wire Dia.	C Outside Width	D Inside Width	Yield Point lbs.
A 6C 8-14	Steel	.353	34	.080	.550	.200	75
A 6C88-14	High Tensile Steel						130
A 6B 8-14	Brass						45
A 6Y 8-14	Stainless						110

SPROCKETS **MATERIAL:** Steel

Catalog Number	No. of Teeth	P.D.	B Bore	E Length	C Hub Dia.	D Hub Proj.	Type
A 6C 8-1409	9	1.03	3/8	13/16	7/8	5/8	Plain
A 6C 8-1411	11	1.25			1-1/8		
A 6C 8-1412	12	1.36	1/2		1-3/16		
A 6C 8-1414	14	1.59					
•A 6C 8-1434	34	3.83			1-1/2		
•A 6C 8-1436	36	4.05					
•A 6C 8-1438	38	4.27					
•A 6C 8-1442	42	4.72					
•A 6C 8-1444	44	4.95					
•A 6C 8-1448	48	5.40			1-3/4		
•A 6C 8-1454	54	6.07					
•A 6C 8-1472	72	8.09					
•A 6C 8-1480	80	8.99					
•A 6C 8-1488	88	9.89					

*Have inserted hub.

Sprockets with: 8 to 11 teeth have a #10-32 set screw.
12 to 88 teeth have a #1/4-20 set screw.

Hydraulic Hand Pumps

10,000 PSI   Winner 1988 SPE* Design Award

Applications

Where portable, hydraulic power is needed, these 10,000 psi hand pumps get the job done with the least effort. With two-speed performance and easy carry design, no other hand pump is easier to use in construction, maintenance, lifting, and testing applications. For use with a wide range of fluids, a multi-fluid version is also available. If remote valves are used, then return-to-tank kits may be ordered for these pumps.

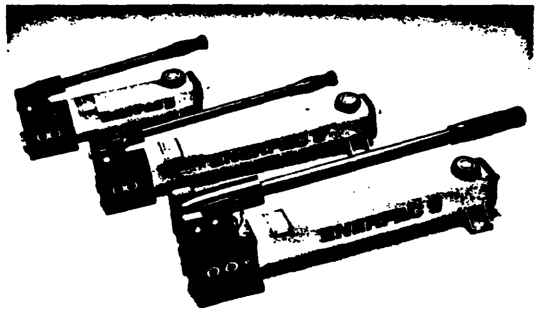
Features

- 6 models.
- Two-speed operation reduces handle strokes by 78% in some cases.
- Durable, rugged glass-filled nylon reservoir resists corrosion; aluminum pump base encapsulated in same glass-filled nylon.
- Lightweight, yet large oil capacities.
- Vented or non-vented performance.
- Dual-purpose fill caps - large opening is easy to fill; cap acts as pressure relief valve in case of accidental reservoir pressurization.
- Reduced handle effort on all models.
- Internal pressure relief valves to protect hydraulic system.
- Non-conductive fiberglass handle.
- Handle lock for easy carrying.

Ordering Information

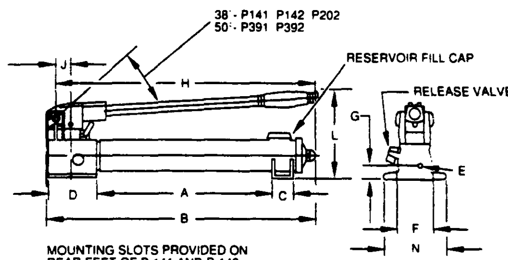
Refer to the selection chart for available models. These pumps are also available in pump, hose, and cylinder sets shown on page 34. P-392 pump available with viton seals - use model no. P-392V.

*Society of Plastic Engineers



P-142, P-202, P-392

PUMP DIMENSIONS

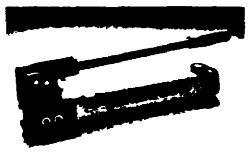


MOUNTING SLOTS PROVIDED ON REAR FEET OF P-141 AND P-142

Accessories

Multi-Fluid Pump

P-392MF



With the same dimensions and performance as the P-392 pump, this pump is designed for multi-fluid applications. The use of viton seals, ceramic balls and stainless steel springs, and advanced coating processes on other parts allows this pump s use with distilled water, water glycols, alcohols, and phosphate esters. Consult factory for specific fluid recommendations.

Tank Kits

PC-20 (For P-141 and P-142 pumps).

PC-25 (For P-202, P-391, and P-392 pumps).

Kit provides 7/16-20 access port at rear of reservoir for use with external valves.

Dimensions (Inches)

Model No.	A	B	C	D	E	F	G	H	J	L	N
P-142	7 5/16	13 1/4	1 1/8	3 1/4	1/4 NPTF	2 9/16	1 1/8	12 9/16	3/4	5 5/8	3 3/4
P-392	13 9/16	21	1 7/16	3 13/16	3/8 NPTF	2 3/4	1 5/16	20 5/16	1 3/16	7	4 3/4
P-202	13 9/16	20 1/16	1 1/16	3 1/4	1/4 NPTF	2 9/16	1 1/8	15 3/4	3/4	5 11/16	3 3/4
P-141	7 5/16	13 1/4	1 1/8	3 1/4	1/4 NPTF	2 9/16	1 1/8	12 9/16	3/4	5 5/8	3 3/4
P-391	13 9/16	21	1 7/16	3 13/16	3/8 NPTF	2 13/16	1 5/16	20 5/16	1 3/16	7	4 3/4

Selection Chart

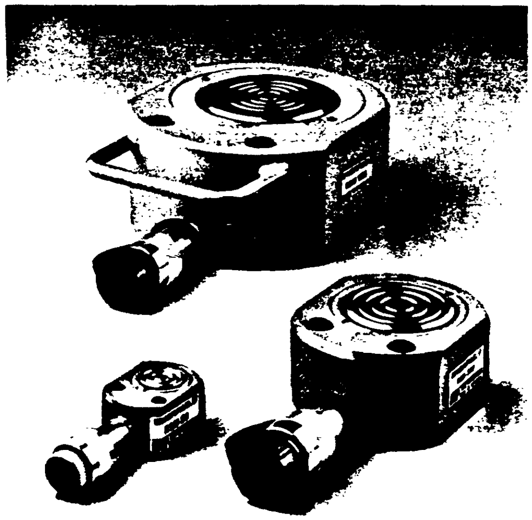
Model No.	Pump Speed	Max. Pressure Rating (PSI)		Res. Cap. (Cu. In.)	Oil Vol. Per Stroke (Cu. In.)	Piston Dia. (In.)	Piston Stroke (In.)	Weight (Lbs.)
P-142	Two-Speed	1st Stage 2nd Stage	200 10,000	20	.221 .055	.75 .38	.50	4.5
P-392	Two-Speed	1st Stage 2nd Stage	200 10,000	55	687 .151	94 .44	1 00	9
P-202	Two-Speed	1st Stage 2nd Stage	200 10,000	55	221 055	.75 .38	50	7.5
P-141	Single-Speed	10,000		20	055	38	50	4.5
P 391	Single-Speed	10,000		55	151	44	1 00	9

Flat-Jac®, Single-Acting Hydraulic Cylinders

RSM Series - 10,000 PSI 5 - 150 Ton Capacities

Applications

The Enerpac Flat-Jac® cylinders are our most compact hydraulic cylinders. With retracted heights starting at only 1 9/32", these handy cylinders are designed for use in tight working areas. Ideal for maintenance and construction applications, many users find these cylinders well suited for production use where other cylinders will not fit.



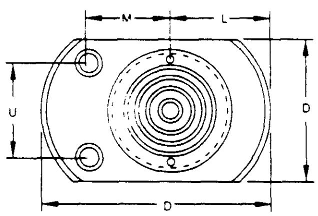
RSM-50, RSM-1000, RSM-300

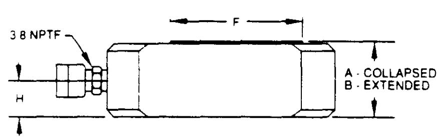
Features

- 8 models.
- Spring return.
- Includes CR-400 coupler and dust cap (except RSM-50 which uses AR-400 coupler)
- Grooved plungers.
- Carrying handles provided on RSM-750, RSM-1000 and RSM-1500.
- Mounting holes permit easy fixturing.
- Baked enamel paint finish provides increased corrosion protection.

Ordering Information

Refer to the selection chart below for the available models. Load holding valves and pressure gauges are some of the optional equipment you may need to order.





Selection Chart

Model No.	Cyl. Cap. (Tons)	Stroke (In.)	Cyl. Effect. Area (Sq. In.)	Oil Cap. (Cu. In.)	A Collapsed Ht. (In.)	B Ext. Ht. (In.)	D Out. Dia. (In.)	Cyl. Bore Dia. (In.)	F Plgr. Dia. (In.)	H Base To Adv. Port. (In.)	Weight (Lbs.)
RSM-50	5	1/4	99	3	1 9/32	1 17/32	2 5/16x1 5/8	1 [illegible]	1	5/8	2.3
RSM-100	10	7/16	2.24	1 0	1 11/16	2 1/8	3 1/4x2 3/8	1 [illegible]	1 1/2	3/4	3.1
RSM-200	20	7/16	4 43	2.0	2 1/32	2 15/32	4x3	2 [illegible]	2	3/4	6.8
RSM-300	30	1/2	6.49	3.2	2 5/16	2 13/16	4 5/8x3 3/4	2 [illegible]	2	3/4	10
RSM-500	50	5/8	9 62	6 0	2 5/8	3 1/4	5 1/2x4 1/2	3 [illegible]	2 3/4	3/4	15
RSM-750	75	5/8	15 90	10 0	3 1/8	3 3/4	6 1/2x5 1/2	4 [illegible]	3 1/4	3/4	25
RSM-1000	100	5/8	19 64	12.2	3 3/8	4	7x6	5	3 5/8	3/4	32
RSM-1500	150	5/8	30.68	17 2	3 13/16	4 1/2	8 1/2x7 1/2	6 [illegible]	4 1/2	1 5/16	58

Mounting Hole Dimensions (Inches)

U	M	L	Mounting Holes (Dia.)
1.12	.88	.81	.191 thru .312 C. Bore, .17 dp
1 44	1.34	1.09	.281 thru .422 C. Bore. .31 dp
1 94	1.56	1.56	.390 thru .594 C Bore, .39 dp
2 06	1.75	1.88	.406 thru .625 C Bore, .44 dp
2.62	2.12	2.25	.469 thru .750 C Bore, .50 dp
3.00	2.62	2.75	.531 thru .812 C. Bore, .56 dp
3.00	2.94	3 00	.531 thru .812 C Bore. .56 dp
4 62	3.25	3.75	.531 thru .812 C Bore, .56 dp

Hydraulic Fittings and Manifolds

10,000 PSI

Fittings

These high-pressure steel fittings are designed for all Enerpac 10,000 psi systems. They can simplify many connections in a hydraulic system. Never use standard pipe fittings or lower pressure rated fittings in a 10,000 psi system.

Recommended Tubing

Enerpac is not the source of high-pressure pipe or tubing, but recommends the use of cold drawn steel tubing instead of regular pipe in the following dimensions:

In place of ¼" pipe. use 17/32" O.D. x 11 ga. (.120") wall.

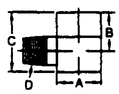
In place of ⅜" pipe. use ⅜" Schedule 80 seamless pipe.

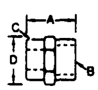
In place of ½" pipe. use 27/32" O.D. x 5/32" wall.

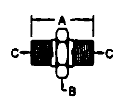
This tubing can be threaded with standard pipe threading dies.

Model No.		Dimensions (In.) A	B	C	D
FZ-1616	Street Elbow	1	5/16	1 7/16	⅜ NPTF
FZ-1615	Reducing Connector	1⅛	⅜ NPTF	¼ NPTF	1¼
FZ-1625		1⅞	½ NPTF	⅜ NPTF	1½
FZ-1608	Hex Nipple	1½	⅝	¼ NPTF	–
FZ-1617		1 13/32	¾	⅜ NPTF	–





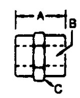


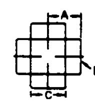
Model No.		Dimensions (In.) A	B	C	D
FZ-1614	Coupling	1 3/16	⅜ NPTF	15/16	–
FZ-1613	Cross	⅞	⅜ NPTF	1	–
FZ-1612	Tee	31/32	⅜ NPTF	1	–
FZ-1610	Elbow	15/16	⅜ NPTF	1	–
FZ-1630	Bushing	¾	⅜ NPTF	9/16	¼ NPTF
FZ-1055	Adaptor	1¾	¼ NPTF	15/16	⅜ NPTF
FZ-1633		1 7/16	¼ NPTF	1⅛	½ NPTF
FZ-1634		1 7/16	⅜ NPTF	1⅛	½ NPTF

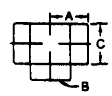


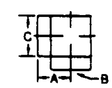


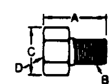












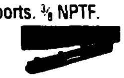
Manifolds

Available in 3 styles. Enerpac manifolds allow for easy connection of multiple cylinders to one pump. Plugs furnished for all ports. ⅜ NPTF.

A-64 - 7" long manifold with 7 female ports.

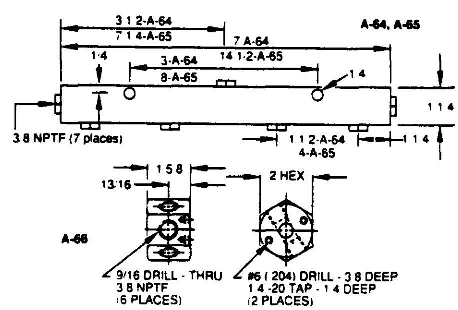
A-65 - 14" long version of A-64 that allows direct mounting of control valves to the manifold.

A-66 - 6-port hexagonal manifold.



A-65

A-66



Premium Hydraulic Oil

Features

- Maximum pump volumetric efficiency.
- Maximum internal heat transfer.
- Prevents pump cavitation.
- Anti-rust, foaming and sludge additives.
- High viscosity index.
- Wide range temperature operation.
- Maximum film protective lubricity.
- Stops oil oxidation.

Selection Chart

Model No.	Capacity
HF 100	One Quart
HF 101	One Gallon
HF 102	Five Gallons
HF 104	Fifty-Five Gallons

Specifications

Viscosity Index	100 min.
Viscosity at 210°F	42/45 S.U.S.
Viscosity at 100°F	150/165 S.U.S.
Viscosity at 0°F	Less than 12,000 S.U.S.
API Gravity	31.0/33.0
Flash, C.O.C.°F	400
Pour Point, °F	-25
Aniline Point °F	210/220
Paraffinic Base Color	Blue

High Pressure Hoses

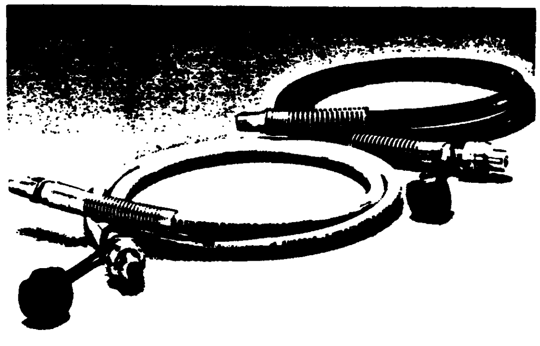
10,000 PSI **Heavy-Duty Rubber or Plastic Coated Nylon**

Applications

Enerpac 10,000 psi hoses are designed for use with all Enerpac 10,000 psi pumps and cylinders. Rugged construction makes these hoses extremely durable, yet highly flexible. Available in 2 basic designs:

Heavy-Duty Rubber - Hose is reinforced with 2 layers of braided steel in lengths up to 50 feet.

Plastic Coated Nylon - A long-lasting hose is ideal for production applications. Available in 6' lengths. (Plastic hoses should be protected from heat and weld spatter.)



HC-963, HC-913

Features

- 41 models.
- ¼" and ⅜" I.D.
- 2' through 50' lengths.

Selection Chart

Model No.	Hose Design	I.D. (In.)	Length (Ft.)	Hose End (1)	Hose End (2)	Weight (Lbs.)
H-900			6	¼ NPTF (Male)	¼ NPTF (Male)	2.6
H-864			6	¼ NPTF (Male)	AH-630	2.9
H-887			6	¼ NPTF (Male)	A-630	3.1
H-870			6	¼ NPTF (Male)	⅜ NPTF (Male)	2.6
H-880			6	⅜ NPTF (Male)	AH-630	2.9
HC-882			6	¼ NPTF (Male)	CH-604	3.0
H-917			2			1.6
H-920			3			1.9
H-909			6	⅜ NPTF (Male)	⅜ NPTF (Male)	2.6
H-926			10			3.9
H-938			20			8.0
H-942			30			13
H-915			2	⅜ NPTF (Male)	⅜ NPTF (Female)	1.4
H-916			2	⅜ NPTF (Male)	AR-400	1.7
H-918		¼	2			1.8
H-921			3	⅜ NPTF (Male)	AH-604	2.1
H-913	Heavy-Duty Rubber (Steel Braided)		6			2.9
H-927			10			4.2
H-922			3			2.4
H-914			6	⅜ NPTF (Male)	A-604	3.2
H-928			10			4.5
HC-921			3			2.2
HC-913			6	⅜ NPTF (Male)	CH-604	3.0
HC-927			10			4.3
HC-941			20			8.3
HC-922			3			2.9
HC-914			6	⅜ NPTF (Male)	C-604	3.7
HC-928			10			5.0
HC-950			50	CH-604	CH-604	20
H-960			6			4.6
H-964			10			7.0
H-972		⅜	20	⅜ NPTF (Male)	⅜ NPTF (Male)	13
H-973			30			21
H-975			50			33
HC-960			6	⅜ NPTF (Male)	CH-604	4.9
HC-964			10			7.3
H-969				⅜ NPTF (Male)	⅜ NPTF (Male)	1.9
H-963				⅜ NPTF (Male)	AH-604	2.1
H-974	Plastic Coated Nylon	¼	6	⅜ NPTF (Male)	A-604	2.4
HC-963				⅜ NPTF (Male)	CH-604	2.2
HC-974				⅜ NPTF (Male)	C-604	2.9

ENERPAC

Instruction Sheet

HYDRAULIC HAND PUMPS AND CYLINDERS

IMPORTANT: RECEIVING INSTRUCTIONS: Visually inspect all components for shipping damage. If any shipping damage is found, notify carrier at once. Shipping damage is NOT covered by warranty. The carrier is responsible for all repair or replacement costs resulting from damage in shipment.

SAFETY FIRST

Carefully plan your system by selecting components designed to perform the intended operation and which will adequately perform with existing equipment. Always check the product limitations regarding pressure ranges, load capacities and set-up requirements. The system operating pressure must not exceed the pressure rating of the lowest rated component in the system. Read all **CAUTIONS, WARNINGS,** and **INSTRUCTIONS** included with, or attached to, each product. Follow all safety precautions to avoid personal injury or property damage during the system operation.

ENERPAC CANNOT BE RESPONSIBLE FOR DAMAGE OR INJURY RESULTING FROM UNSAFE PRODUCT USE, LACK OF MAINTENANCE OR INCORRECT PRODUCT AND SYSTEM APPLICATION. Contact ENERPAC ENGINEERING when in doubt as to safety precautions, or applications.

CAUTION:
Make sure that the highest level of system pressure does not exceed the lowest pressure rating of any component within the system.

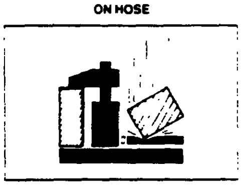
The following general instructions and guides will be helpful to determine if your system components are properly connected:

1. Be sure all hydraulic connections, hoses, fittings are rated for the highest pressure your system is capable of generating. Always use hoses and tubing recommended by the hydraulic component manufacturer.
2. Be sure all connections are fully tightened. Seal all pipe connections with a high-grade pipe thread sealer.

   CAUTION: Teflon tape is an excellent thread sealer, however, if the tape is not properly applied, pieces may enter the hydraulic system causing malfunctions and damage. Use 1½ wraps of tape on each thread. Cut off all loose tape ends.
3. **DO NOT** over-tighten any connections. All connections should be snug and leak-free. Excessive tightening will cause strain on the threads and castings which could cause fitting failure at pressures below rated capacity.
4. Fully tighten hydraulic couplers (avoid excessive force). Loose couplers will act as a partial or complete line restriction causing little or no oil flow and resulting in equipment damage or failure.
5. Be sure all hydraulic hoses and fittings are connected to the correct **Inlet** and **outlet** ports of the pump, cylinder, valves and other system components.

RECOMMENDATION: Use hydraulic gauges which indicate safe operating loads in each hydraulic system. Gauges are available for use with all hydraulic components (some gauges have a colored band to indicate load ranges for each cylinder.) **DO NOT** exceed the safe limit of the lowest rated component used within your system.

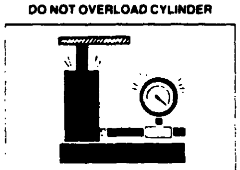
DO NOT DROP HEAVY OBJECTS ON HOSE



A sharp impact may cause bends or breaks to internal hose wire strands. Applying pressure to the damaged hose will cause internal flexing which will eventually break the hose strands causing the hose to rupture.

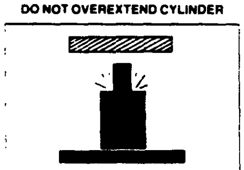
DO NOT use the hydraulic hose to carry a hydraulic component (i.e. pumps, cylinders and valves).

DO NOT OVERLOAD CYLINDER



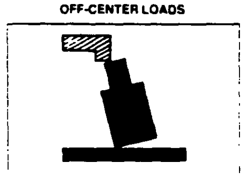
Never attempt to lift a load which exceeds the capacity of a cylinder or jack. Overloading causes equipment failure and possible personal injury.

DO NOT OVEREXTEND CYLINDER



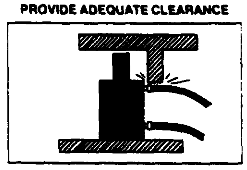
The cylinder will take full load on the plunger stop ring. However, using the full stroke does not supply power and only adds unnecessary strain to the cylinder.

OFF-CENTER LOADS



Avoid situations where loads are not directly centered on the cylinder plunger. Off-center loads produce considerable strain on cylinder plungers and may slip or fail causing potentially dangerous results. Avoid point loading — Distribute the load evenly across the entire saddle surface.

PROVIDE ADEQUATE CLEARANCE

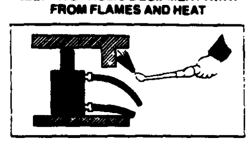


Always provide clearance for hoses and couplers to avoid moving objects, abrasion or sharp objects.

AVOID SHARP BENDS AND KINKS IN HOSE

Avoid sharp bends and kinks when routing hydraulic hoses. If pressure is applied to a bent or kinked hose, the oil flow will be restricted causing severe back-pressure. Also the sharp bends and kinks will internally damage the hose leading to premature failure.

KEEP HYDRAULIC EQUIPMENT AWAY FROM FLAMES AND HEAT



Excessive heat (above 150° F) will soften packings and seals, resulting in fluid leaks. Heat also weakens hose materials and packings. For optimum performance **DO NOT** expose equipment to temperatures of 150° F or higher.

TO PROTECT YOUR WARRANTY, USE ONLY ENERPAC HYDRAULIC OIL.

PUMP SELECTION

All hydraulic cylinders must be properly connected to the source of hydraulic oil to operate. This source is generally a hand-operated or power-operated pump. The choice of pump will depend upon the requirements of your application. ENERPAC has available pumps to match cylinders for your applications.

Use the correct pump for the cylinder you have.

VALVING: For **Single-Acting** cylinders, use a pump with a 2-way or 3-way valve and one hose.

For **Double-Acting** cylinders, use a pump with a 4-way valve and two hoses.

OIL CAPACITY: Always use a pump that has an oil reservoir sufficient to fully advance or retract your cylinder.

PUMP TYPES:

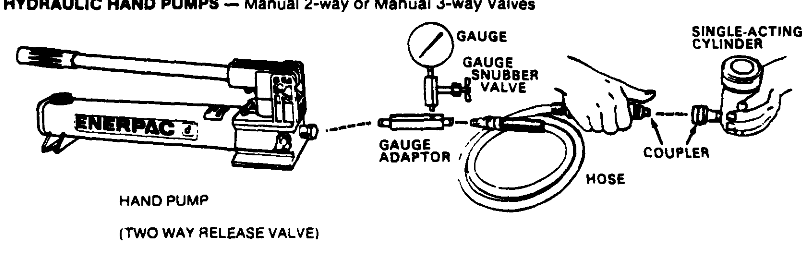
Hand Pumps — Use Hand pumps for low speed cylinder applications.

Power Pumps — Use a power pump for applications requiring higher speeds and for large cylinders.

MODEL NUMBER	TYPE	PRESSURE RATING (PSI)	RESERVOIR CAPACITY (Cu.In.)	OIL VOLUME PER STROKE (Cu.In.)	PISTON DIA. (In.)	PISTON STROKE (In.)
P-141	SINGLE SPEED	0 to 10,000	20.0	.05	3/8	1/2
P-18	SINGLE SPEED	0 to 2,850	22.0	.16	1/2	13/16
P-391	SINGLE SPEED	0 to 10,000	55.0	.151	7/16	1
P-51	SINGLE SPEED	0 to 3,000	50.0	.25	9/16	1
P-80	TWO SPEED	0 to 350 350 to 10,000	140.0	.99 .15	1-1/8 7/16	1
P-84	TWO SPEED	0 to 350 350 to 10,000	140.0	.99 .15	1-1/8 7/16	1
P-142	TWO SPEED	0 to 200 200 to 10,000	20.0	.221 .055	3/8 3/4	1/2
P-202	TWO SPEED	0 to 200 200 to 10,000	55	.221 .055	3/8 3/4	1/2
P-392	TWO SPEED	0 to 200 200 to 10,000	55	.687 .151	7/16 15/16	1
P-462	TWO SPEED	0 to 200 200 to 10,000	462.0	7.69 .29	2-5/8 1/2	1-1/2
P-464	TWO SPEED	0 to 200 200 to 10,000	462.00	7.69 .29	2-5/8 1/2	1-1/2

How to Assemble Single-Acting Hydraulic Cylinders to Pumps

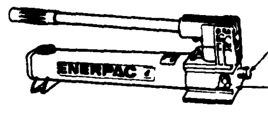
HYDRAULIC HAND PUMPS — Manual 2-way or Manual 3-way Valves



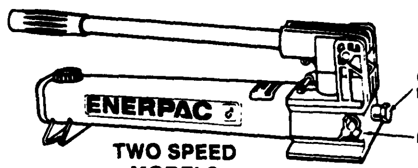
NOTE: Hand pump fill cap has two positions, ¼ turn for venting or ½ turn to close.

FOR SINGLE ACTING CYLINDERS

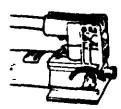
Operating Hydraulic Hand Pumps with Integral Release Valves



SINGLE SPEED MODELS

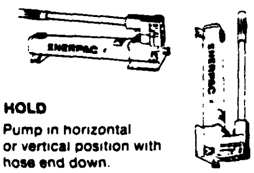


TWO SPEED MODELS



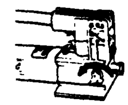
ADVANCE

1. Close release valve finger-tight by turning handle (near hose end of pump) clockwise.
2. Operate pump handle.



HOLD

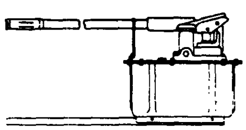
Pump in horizontal or vertical position with hose end down.



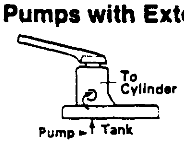
RETRACT

Open release valve by turning handle (near hose end of pump) counterclockwise.

Operating Hydraulic Hand Pumps with External Valves

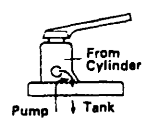


AUTOMATIC TWO-SPEED



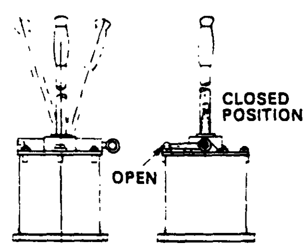
ADVANCE

Close release valve by turning handle clockwise.



RETRACT

Open release valve by turning handle counterclockwise.



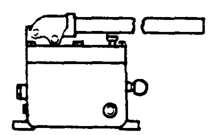
SINGLE-SPEED

ADVANCE

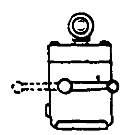
Close release valve by turning handle clockwise.

RETRACT

Open release valve by turning handle counterclockwise.

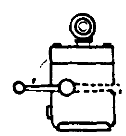


SINGLE-SPEED



ADVANCE

Close release valve by turning handle clockwise.



RETRACT

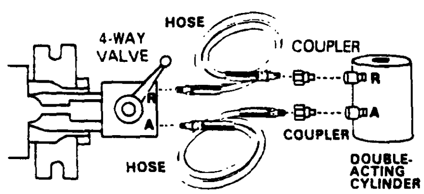
Open release valve by turning handle counterclockwise.

FOR DOUBLE ACTING CYLINDERS

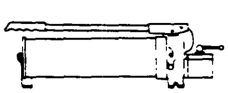
How to Assemble Double-Acting Hydraulic Cylinders to Pumps

HYDRAULIC HAND PUMP

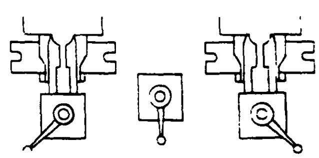
Manual 4-way Valves

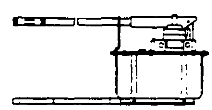


Operation of Hand Pumps (Two Speed) with Pump Mounted External Valves

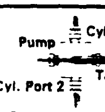


AUTOMATIC TWO-SPEED

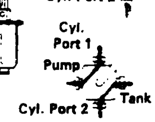




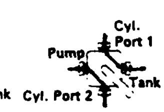
AUTOMATIC TWO-SPEED



HOLD



ADVANCE

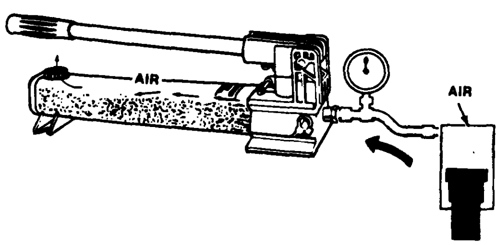


RETRACT

OPERATION

REMOVAL OF AIR

When hoses, cylinders and other components are connected to build a system, air will be trapped in the system. To function properly, the air in the system must be removed. However, the hand pump does require air in the reservoir to prevent a vacuum. If the pump reservoir is totally filled and the vent cap is closed tight, the vacuum created will prevent oil flow out of the pump. Fill reservoirs only to level indicated on the pump end cap.



SINGLE ACTING CYLINDER SYSTEMS

1. After all system components are connected to the hand pump, check reservoir oil level. Fill to indicator mark on the end cap. Replace the fill cap and be sure it is closed (not in vent position).
2. Turn pump release valve to closed position. Operate hand pump until cylinder plunger is completely extended.
3. Invert cylinder (plunger end down). Open the pump release valve. as the plunger retracts, the air in the system will be forced into the pump reservoir and replaced by oil. Close the release valve.
4. Turn the cylinder upright. Operate the pump to cycle the cylinder plunger. If air is out of the system, the plunger will advance and retract smoothly. If the plunger is erratic, repeat steps 1 through 4.
5. Open the pump fill cap and check the oil level. Fill to the indicator mark on the end cap.

DOUBLE ACTING CYLINDERS

1. After all system components are connected to the hand pump check pump reservoir oil level. Fill to the indicator mark on the pump end cap. Replace end cap and tighten (not in vent position).
2. Place hand pump in a place where it will be higher than the hydraulic cylinder. Lay the hydraulic cylinder on its side with the couplers facing up.
3. Close the pump release valve (finger tight). Operate the pump to advance and retract the cylinder plunger three or four times.
4. Open pump release valve to retract the cylinder plunger Check pump oil level. Add oil as necessary to restore correct level in the reservoir.

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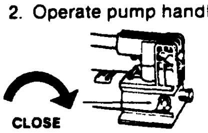
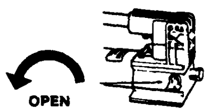
1. To advance cylinder plunger, turn pump release valve clockwise as illustrated and close **finger-tight.** CAUTION: To avoid release valve damage, do not use tools to tighten valve.
2. Operate pump handle.



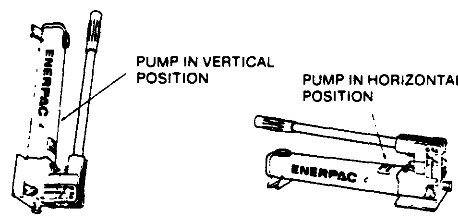
ADVANCE



RETRACT

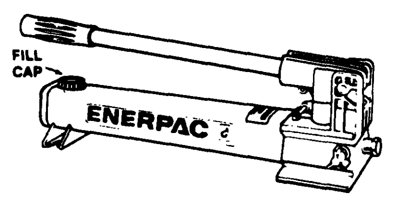
3. To retract cylinder plunger, turn release valve counterclockwise as illustrated.

4. Pump can be operated from horizontal or vertical (as long as hose end is down.)



MAINTENANCE

To check oil level in pump, open pump release valve to allow oil in cylinder (if connected) to return to pump. Remove fill cap. Add ENERPAC hydraulic oil until level with mark on rear cap. **DO NOT** overfill. To function properly all hand pumps require air int he reservoir. If oil level is too high the pump will not operate. If hydraulic system is used under extremely dirty conditions, frequently drain pump completely. Refill with clean ENERPAC hydraulic oil. Install fill cap and close it.



REPLACING COUPLER

ASSEMBLING TO HOSE (FIGURE #1)

Clamp the hexagon nut of the hose fitting in a vise as illustrated. Remove the old coupler or rigid adaptor. Install new coupler clockwise on to hose fitting to a firm fit. Use high quality thread sealer on threads (one wrap only).
A kit has been prepared for the purpose of replacing a worn out seal and may be obtained at your nearest authorized technical service center.

ASSEMBLING SPEE-D-COUPLERS TO CYLINDER (FIGURE #2)

Use wrench to unscrew old coupler half from cylinder. Thread new coupler to cylinder and tighten firmly. Use a high quality thread sealant on coupler thread (one wrap only).

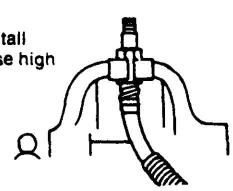


FIGURE #1

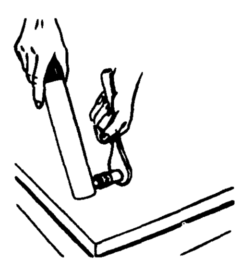
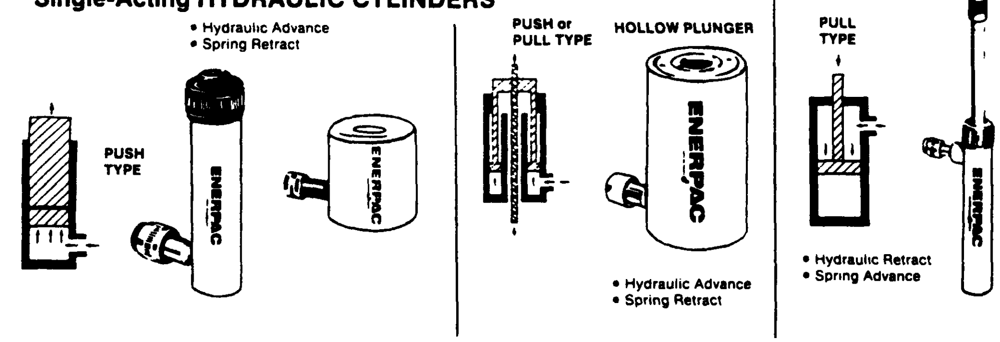


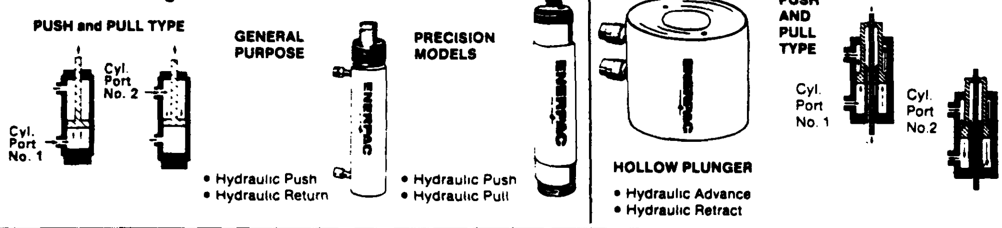
FIGURE #2

HYDRAULIC CYLINDERS

Single-Acting HYDRAULIC CYLINDERS



Double-Acting HYDRAULIC CYLINDERS

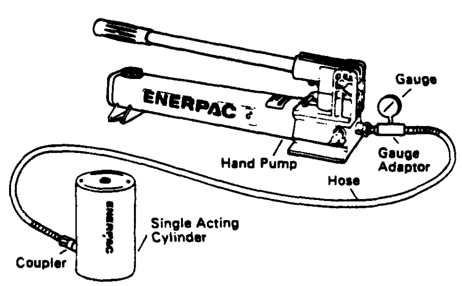


GENERAL INSTRUCTIONS

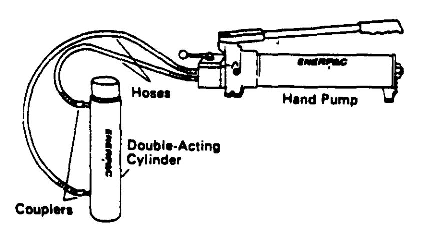
ENERPAC cylinders are designed for full rated capacity over the full plunger travel. Refer to current ENERPAC catalog for capacity.

OPERATIONAL INSTRUCTIONS

Hydraulic Connections — All hydraulic cylinders must be properly connected to the hydraulic pump to function. Always use thread sealant on connections (i.e., teflon tape or equivalent). The following diagram shows the basic connections of hydraulic cylinders to pumps.

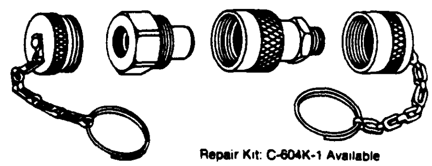


1. Hand Pump — Two-way Release Valve
2. Hose — One required
3. Coupler — Male half coupler on hose
4. Single-Acting Cylinder — hydraulic force in one direction only. Female half coupler on cylinder.

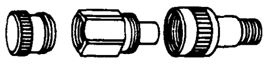


1. Hand Pump — Four-way Valve (Pump Mounted)
2. Hose — Two required
3. Coupler — Male half coupler on each hose
4. Double-Acting Cylinder — Hydraulic force in advance and retract. Two female half couplers on cylinder.

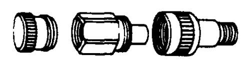
3/8" HIGH FLOW COUPLER



3/8" REGULAR COUPLER

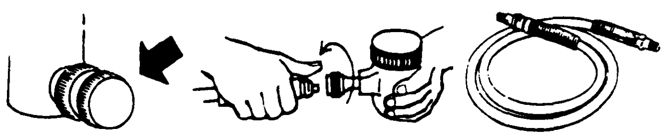


1/4" COUPLER



KEEP OIL LINES CLEAN

When coupler halves are disconnected, always screw on dust caps. Use every precaution to guard unit against entrance of dirt because dirt and foreign matter may cause pump, cylinder or valve failure.



TROUBLE SHOOTING

STEP NO. 1: Advance the hydraulic cylinder into its fullest extension. If the cylinder does not fully advance, refer to Problems No. 1 and 2 below.

STEP NO. 2: After the cylinder is advanced, continue to pump until the gauge shows approximately 3,000 PSI of hydraulic pressure. If 3,000 PSI cannot be obtained, refer to Problem No. 5 below.

STEP NO. 3: After 3,000 PSI is obtained, put your hydraulic system into the hold position. If the pressure drops rapidly, refer to Problem No. 5 below.

PROBLEM	POSSIBLE CAUSE
1. Cylinder will not advance	A. Pump release valve open B. No oil in pump C. Air bound D. Couplers not fully tightened E. Blocked hydraulic line F. Pump not operating
2. Cylinder advances part way	A. Oil level in pump is low B. Cylinder plunger binding C. Air trapped in cylinder
3. Cylinder advances in spurts	A. Air in hydraulic system B. Cylinder plunger binding
4. Cylinder advances slower than normal	A. Leaking connection B. Restricted hydraulic line or fitting C. Loose coupler D. Pump malfunctioning
5. Cylinder advances but will not hold pressure	A. Cylinder seals leaking B. Leaking connection C. Pump malfunctioning D. Incorrect system set-up
6. Cylinder leaks oil	A. Worn or damaged seals B. Loose connection C. Internal cylinder damage
7. Cylinder will not retract or retracts slower than normal	A. Pump release closed B. Coupler not fully closed C. Blocked hydraulic line D. Broken retraction spring E. Pump reservoir over-filled F. Cylinder damaged internally
8. Cylinder will not fully retract	A. Weak retraction spring B. Pump reservoir over-filled C. Partially blocked hydraulic line D. Damaged internally or externlly

REPAIR AND SERVICE INSTRUCTIONS: For repair service and parts contact your nearest ENERPAC Authorized Technical Service Center. The ENERPAC Technical Service Center will provide complete and prompt service on all ENERPAC products. For the location of an ENERPAC Service Center, call **Toll Free 1-800-433-2766. (In Canada CALL 1-800-268-6975)**

NOTE: This phone number is not for product repair information.

For service related information contact ENERPAC Service Department 1-414-781-6600

PARTS AND SERVICE: For quality workmanship and genuine ENERPAC parts select an Authorized ENERPAC Technical Service Center for your repair needs. Only repairs performed by an Authorized Service Center displaying the official ENERPAC sign are backed with full factory warranty. The Classified Section in Your Phone Book lists your nearest Service Center.

All ENERPAC tools are guaranteed from date of delivery to user against defects in workmanship and materials. Free repair or replacement will be made on all items not standing up to this guarantee. Following manufacturers trade customs, however, chains cannot be guaranteed. Warranty does not cover ordinary wear and tear, abuse or misuse, overloading, altered products or use of improper fluids. For prompt handling, send items requiring repairs prepaid, to your nearest ENERPAC authorized service center.

WARRANTY RETURN PROCEDURE: When question of warranty claim arises, the user should send his unit to the nearest ENERPAC Authorized Technical Service Center for inspection, transportation to be prepaid and evidence of purchase date furnished. If the claim comes under the terms of our warranty, the Authorized Technical Service Center will REPAIR OR REPLACE PARTS AFFECTED and return prepaid.

ENERPAC®

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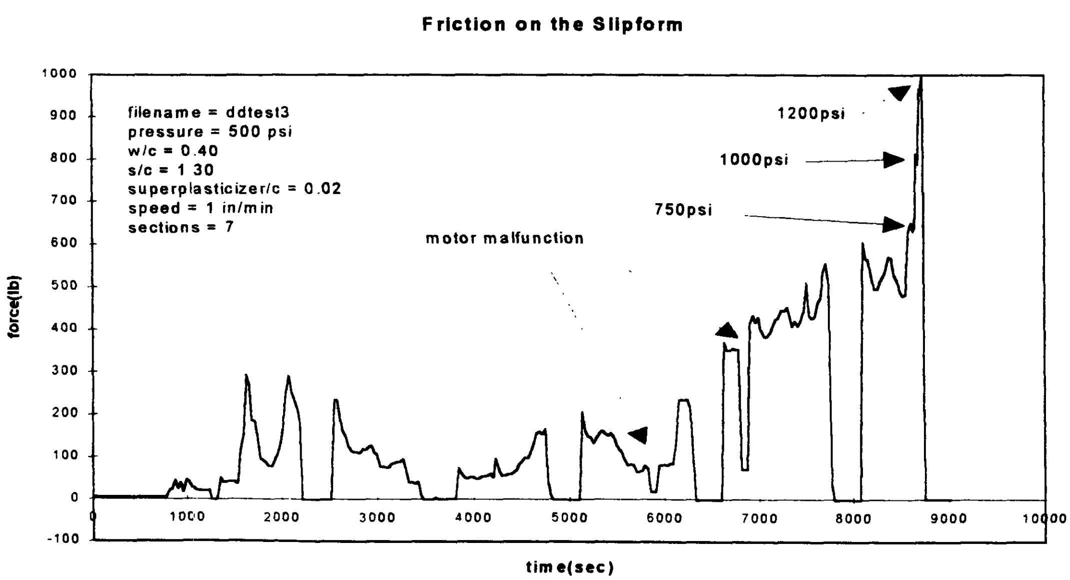
Appendix E

Records of the Tests

Record of Experiments

Date	Apr.13,95			
Filename	ddtest3			
Pressure	500psi			
Speed	1in/min			
Concrete Mix		w/c		0.4
		s/c		1.3
		superplaticizer/c		0.02
Sections	Motor	Time	Remark	
1	Start	2:56		
	Stop	3:00		
2	Start	3:05		
	Stop	3:20		
3	Start	3:25		
	Stop	3:41		
4	Start	3:46	add a pad to hydraulic cylinder 1, squeeze down	
	Stop	4:03		
5	Start	4:08	add a pad to hydraulic cylinder 2	
	Stop	4:18	motor malfunction(set screw)	
	Start	4:22	repaired	
	Stop	4:28	bolts loose, tighten it at 4:26	
6	Start	4:33	add a pad to hydraulic cylinder 3	
	Stop	4:35	motor malfunction(set screw)	
	Start	4:38	repaired	
	Stop	4:52		
7	Start	4:58	add a pad to hydraulic cylinder 4	
	Stop	5:08	5:04 start to change pressure	
		end of test		

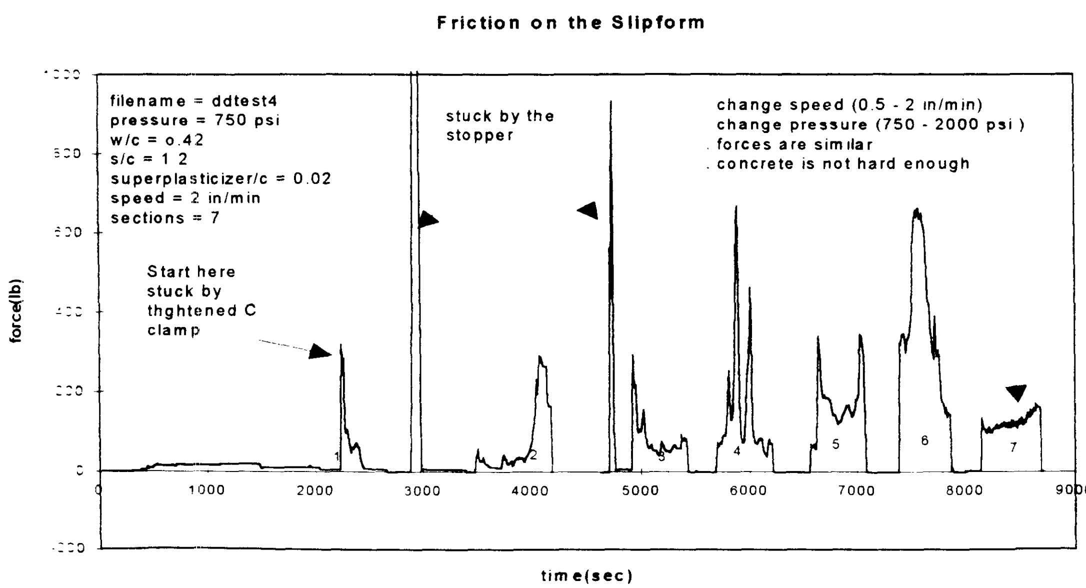


Record of Experiments

Date	Apr14,95
Filename	ddtest4
Pressure	750psi
Speed	2in/min

Concrete Mix		
	w/c	0.42
	s/c	1.2
	superplaticizer/c	0.02

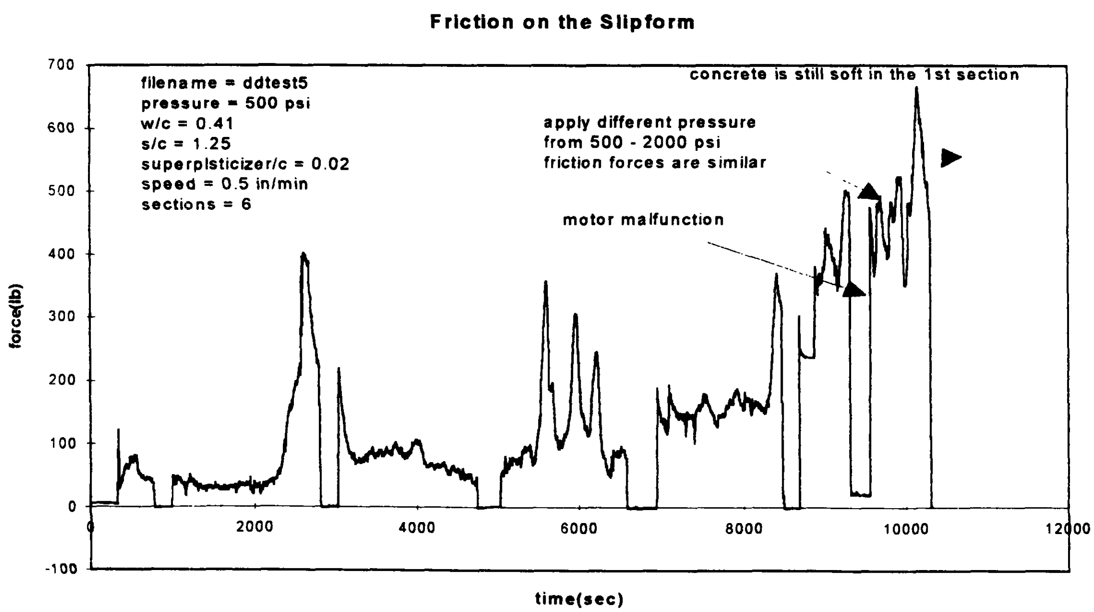
Sections	Motor	Time	Remark
1	Start	12:15	
	Stop	12:18	
2	Start	12:25	
	Stop	12:36	stuck by the stopper
	Start	12:40	repaired
	Stop	12:46	
3	Start	12:57	
	Stop	12:58	stuck by the stopper
	Start	1:00	repaired
	Stop	1:08	
4	Start	1:13	add a pad to hydraulic cylinder 1, squeeze down
	Stop	1:21	
5	Start	1:27	add a pad to hydraulic cylinder 2, squeeze down
	Stop	1:36	
6	Start	1:41	add a pad to hydraulic cylinder 3
	Stop	1:50	
7	Start	1:54	add a pad to hydraulic cylinder 4
	Stop	2:02	1:52 change speed and pressure
		end of test	



Record of Experiments

Date	Apr.14.95		
Filename	ddtest5		
Pressure	500psi		
Speed	0.5in/min		
Concrete Mix		w/c	0.41
		s/c	1.25
		superplaticizer/c	0.02

Sections	Motor	Time	Remark
1	Start	4:00	
	Stop	4:06	
2	Start	4:10	
	Stop	4:40	
3	Start	4:44	
	Stop	5:12	
4	Start	5:18	add a pad on hydraulic cylinder 1, squeeze down
	Stop	5:43	5:26 tighten bolts, force goes up to 300lbs and down.
5	Start	5:49	add a pad on hydraulic cylinder 2
	Stop	6:15	
6	Start	6:21	add a pad on hydraulic cylinder 3
	Stop	6:30	motor malfunction(set screw)
	Start	6:33	repaired, test different pressure
	Stop	6:45	
		end of test	

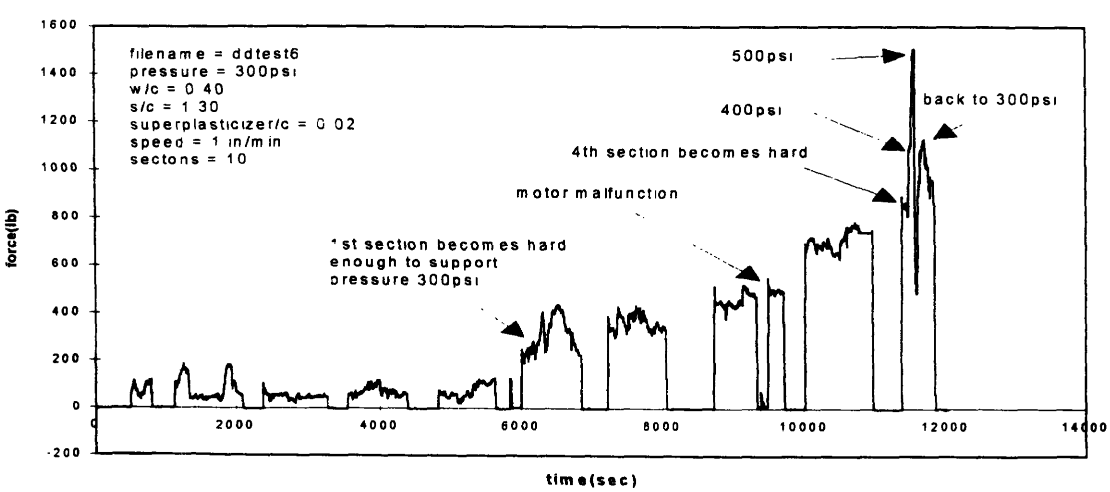


Record of Experiments

Date	Apr.16,95		
Filename	ddtest6		
Pressure	300psi		
Speed	1 in/min		
Concrete Mix		w/c	0.4
		s/c	1.3
		superplaticizer/c	0.02

Sections	Motor	Time	Remark
1	Start	2:57	
	Stop	3:02	
2	Start	3:08	
	Stop	3:21	
3	Start	3:29	
	Stop	3:43	
4	Start	3:48	add a pad on hydraulic cylinder 1, squeeze down
	Stop	4:01	
5	Start	4:09	add a pad on hydraulic cylinder 2
	Stop	4:23	
6	Start	4:29	add a pad on hydraulic cylinder 3
	Stop	4:43	1st section hard
7	Start	4:50	add a pad on hydraulic cylinder 4
	Stop	5:03	2nd section hard
8	Start	5:14	add a pad on hydraulic cylinder 5, 3rd section hard
	Stop	5:25	motor malfunction(set screw)
	Start	5:27	
	Stop	5:31	
9	Start	5:36	add a pad on hydraulic cylinder 6
	Stop	5:49	
10	Start	5:58	add a pad on hydraulic cylinder 7, 4th section hard
	Stop	6:06	change pressure

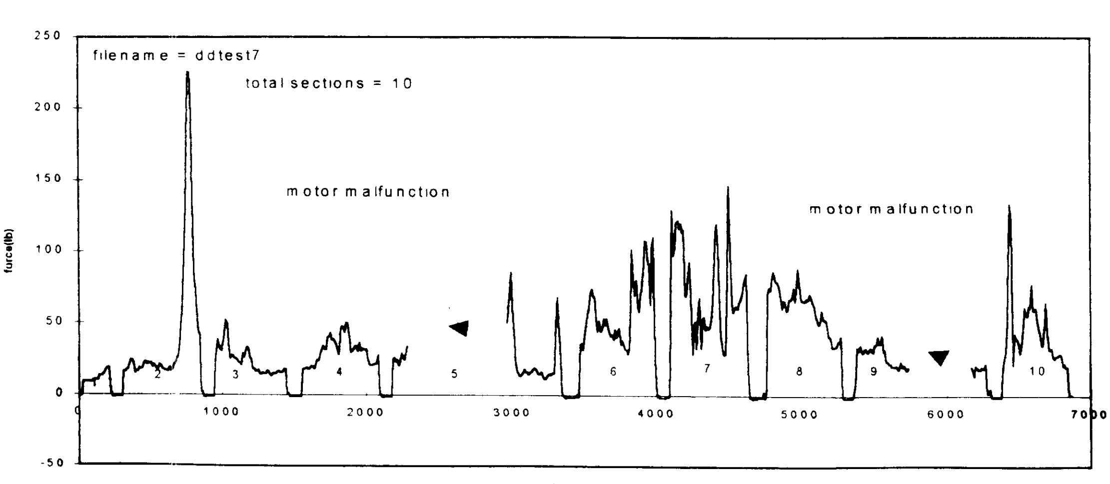
Friction on the Slipform



Record of Experiments Empty test (without concrete)

Date	Apr.17,95		
Filename			
Pressure			
Speed			
Concrete Mix		w/c	
		s/c	
		superplaticizer/c	
Sections	Motor	Time	Remark
1	Start		
	Stop		
2	Start		
	Stop		tight at the end
3	Start		
	Stop		
4	Start		
	Stop		
5	Start		motor malfunction(set screw)
	Stop		
6	Start		
	Stop		
7	Start		
	Stop		
8	Start		
	Stop		
9	Start		motor malfunction(set screw)
	Stop		
10	Start		
	Stop		
		end of test	

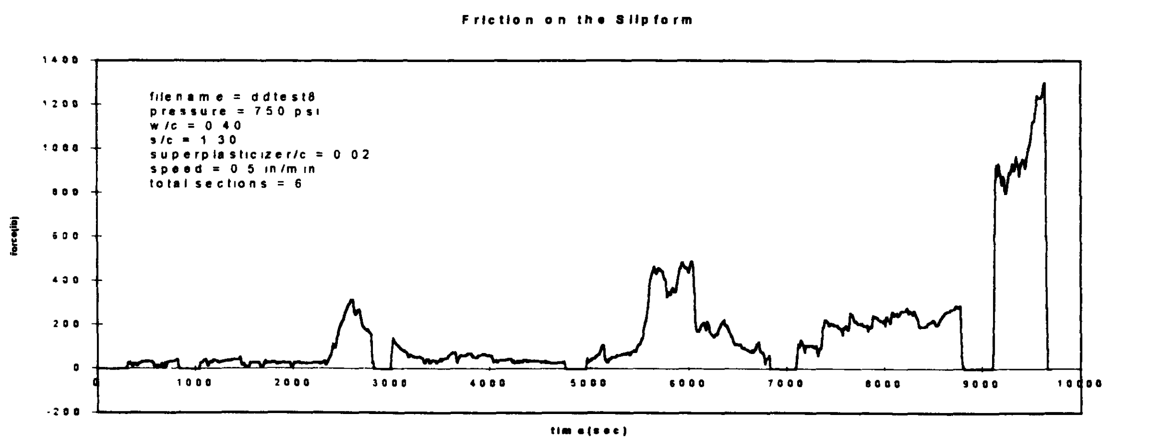
Friction of the Testing Device

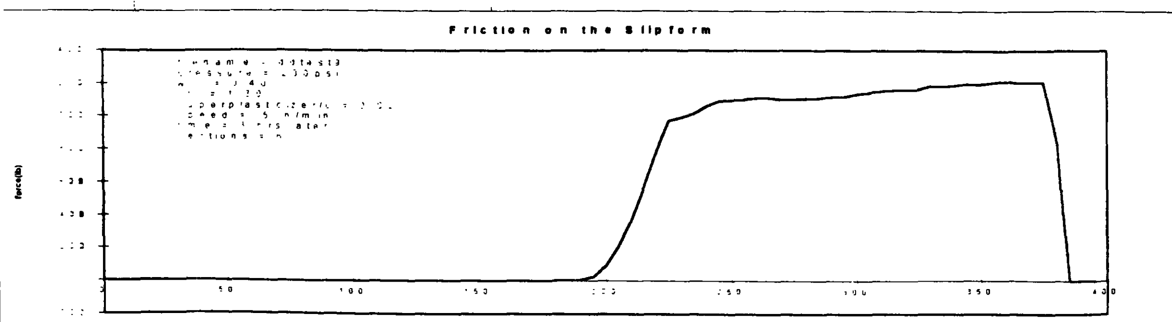


Record of Experiments

Date	Apr.17,95			
Filename	ddtest8			
	ddtest9			
Pressure		750psi		
Speed		0.5in/min		
Concrete Mix		w/c		0.4
		s/c		1.3
		superplaticizer/c		0.02

Sections	Motor	Time	Remark
1	Start	10:10	
	Stop		
2	Start		
	Stop		
3	Start		
	Stop		
4	Start		add a pad on hydraulic cylinder 1, squeeze down
	Stop		
5	Start		add a pad on hydraulic cylinder 2
	Stop		
6	Start		add a pad on hydraulic cylinder 3, 1st section hard
	Stop		
		start ddtest9	
6	Start	1:10	pressure = 200 psi
	Stop	1:14	



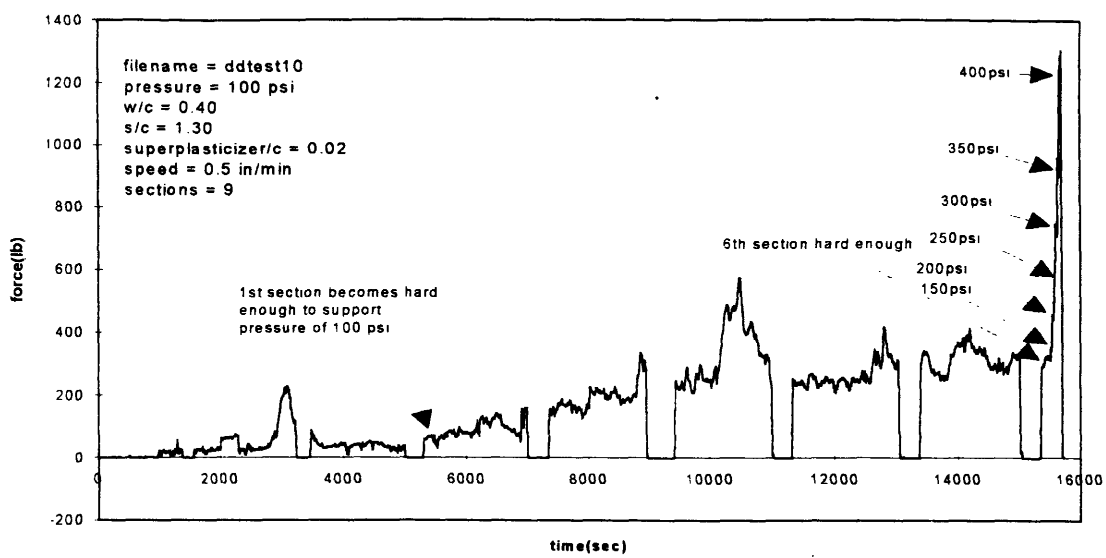


Record of Experiments

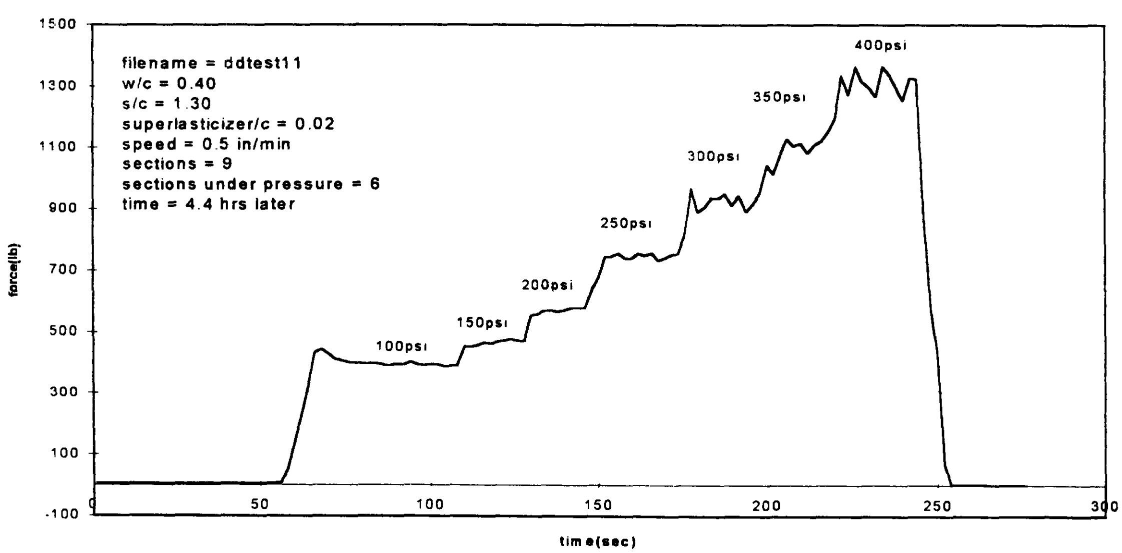
Date	Apr.22.95		
Filename	ddtest10.11,12,13		
Pressure	100psi		
Speed	0.5in/min		
Concrete Mix		w/c	0.4
		s/c	1.3
		superplaticizer/c	0.02

Sections	Motor	Time	Remark
1	Start	1:53	
	Stop	1:59	
2	Start	2:03	
	Stop	2:30	
3	Start	2:34	
	Stop	3:00	
4	Start	3:05	add a pad on hydraulic cylinder 1, section 1 hard
	Stop	3:33	
5	Start	3:39	add a pad on hydraulic cylinder 2, section 2 hard
	Stop	4:07	
6	Start	4:13	add a pad on hydraulic cylinder 3, section 3 hard
	Stop	4:40	
7	Start	4:45	add a pad on hydraulic cylinder 4, section 4 hard
	Stop	5:13	
8	Start	5:19	add a pad on hydraulic cylinder 5, section 5 hard
	Stop	5:46	
9	Start	5:52	add a pad on hydraulic cylinder 6, section 6 hard
	Stop	5:59	5:53 change pressure
		start ddtest 11	
9	Start	6:17	change pressure
	Stop		
		start ddtest 12	
9	Start	6:40	add pads on hydrulic cylinders 7 & 8, change pressure
	Stop		sections 7 & 8 hard
		start ddtest13	
9	Start	6:55	change pressure
	Stop		
		end of test	

Friction on the Slipform



Friction on the Slipform



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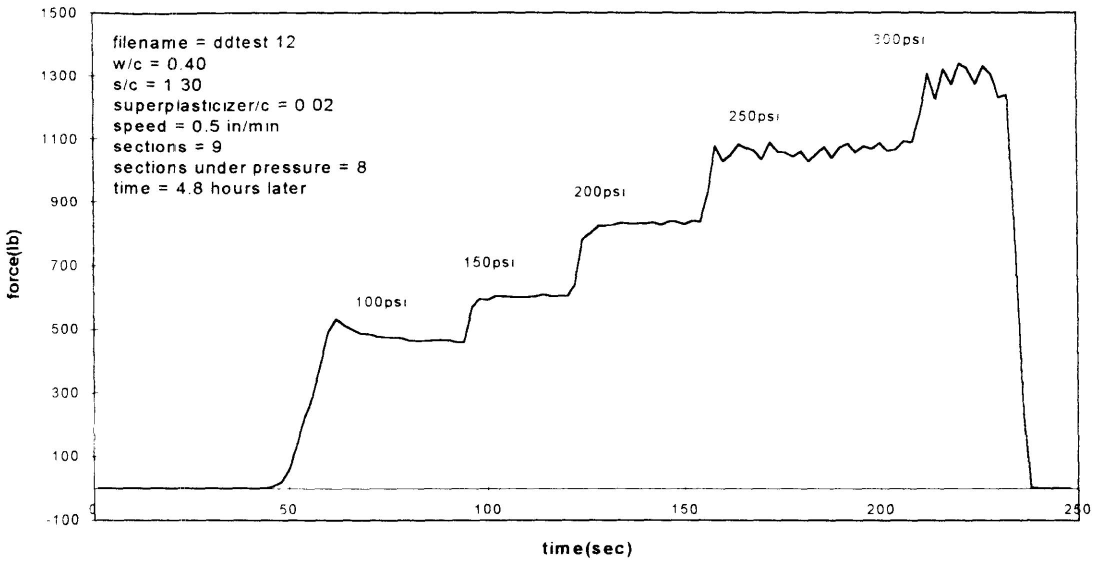

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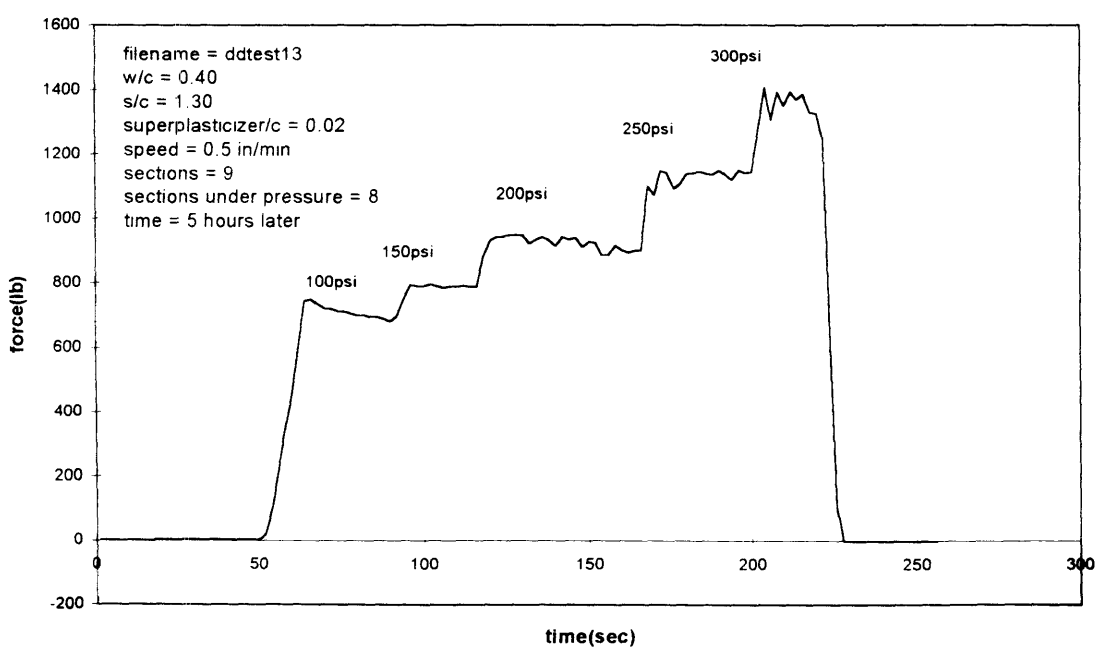

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